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Single π^0 production by $\bar{\nu}_\mu$ charged-current interactions in plastic scintillator

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Introduction

- ◆ Discovery of neutrino oscillations
 - Neutrinos have masses and they mix
 - Physics beyond the Standard Model
- ◆ Recent measurements of non-zero θ_{13} open possibilities to discover CP violation in the lepton sector
- ◆ CP asymmetry

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \sim \sin 2\theta_{13} \sin \delta_{CP}$$

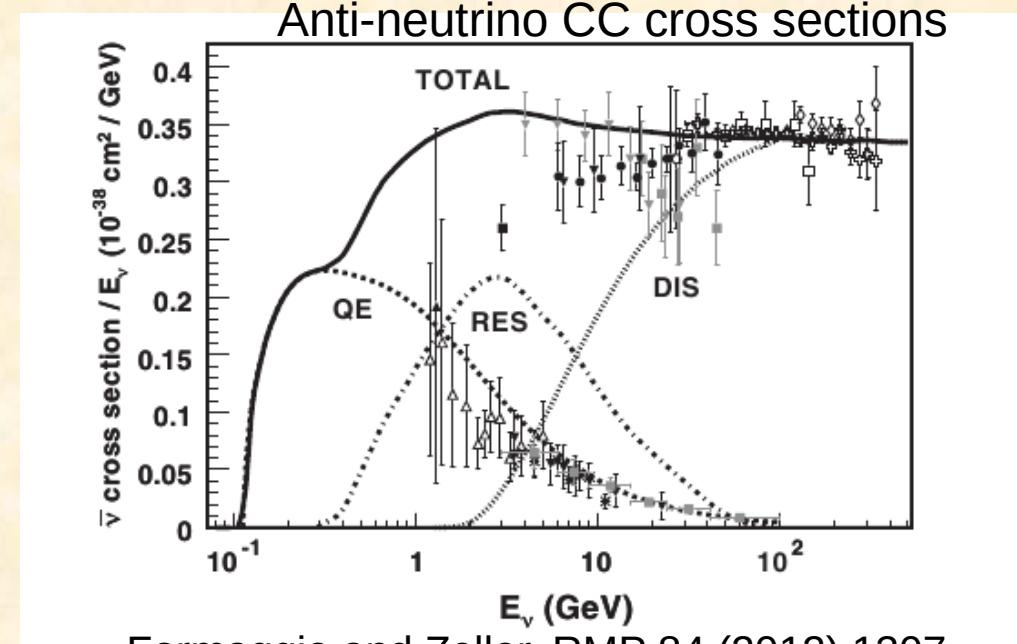
- ◆ Require measurements of anti-neutrino as well as neutrino appearance probabilities



Neutrino interactions

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- ◆ Oscillation experiments measure neutrino flavors (e, μ, τ) through charged-current (CC) interactions
- ◆ In the few GeV region of E_ν , several very different CC processes are operative:
 - Quasielastic
 - Resonant
 - Deep inelastic scattering
- ◆ Cross sections for these processes must be accurately determined in order that precise oscillation measurements become feasible



Formaggio and Zeller, RMP 84 (2012) 1307



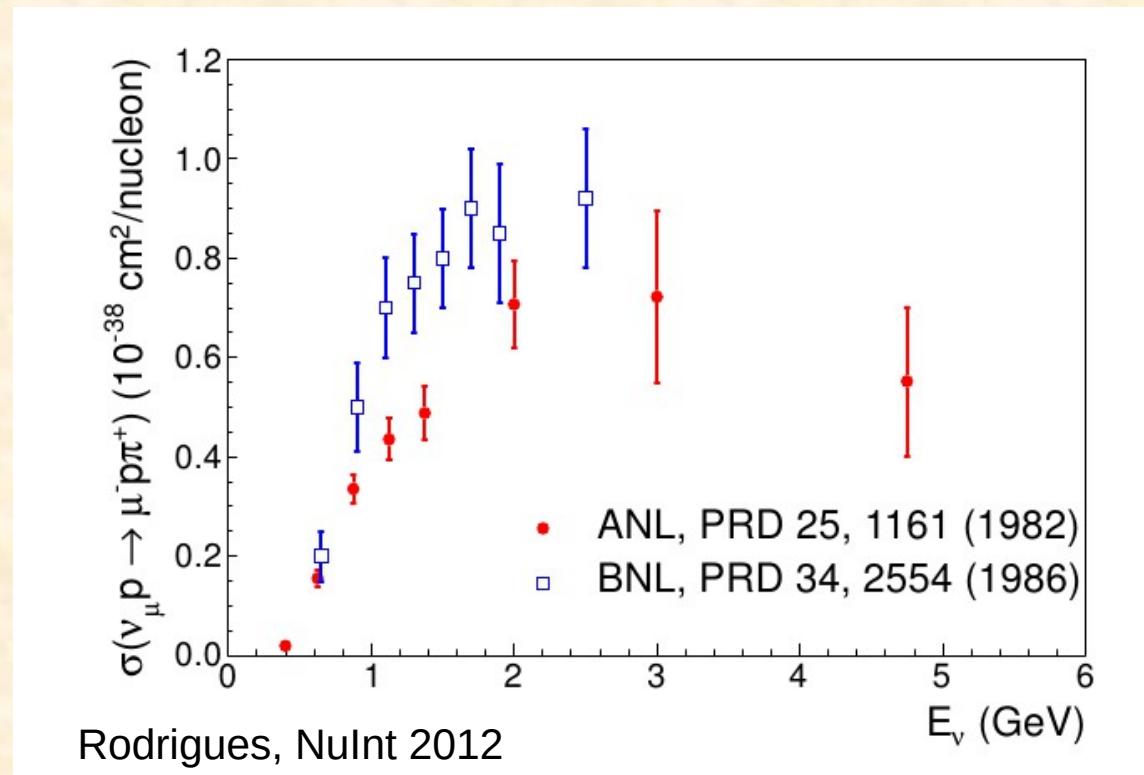
Single pion production

- ◆ Single pion production is dominated by nucleon resonances
- ◆ Backgrounds in oscillation experiments
 - Charged-current pion production followed by absorption is similar to CC quasielastic signal
 - Neutral-current π^0 production can mimic ν_e appearance signal
- ◆ Pion production channels important at NOvA and LBNE energies
- ◆ Theoretical interest, hadronic physics
 - Pion in nuclei



Previous measurements using neutrinos

- ◆ Old measurements using bubble chambers on deuterium (ANL, BNL)



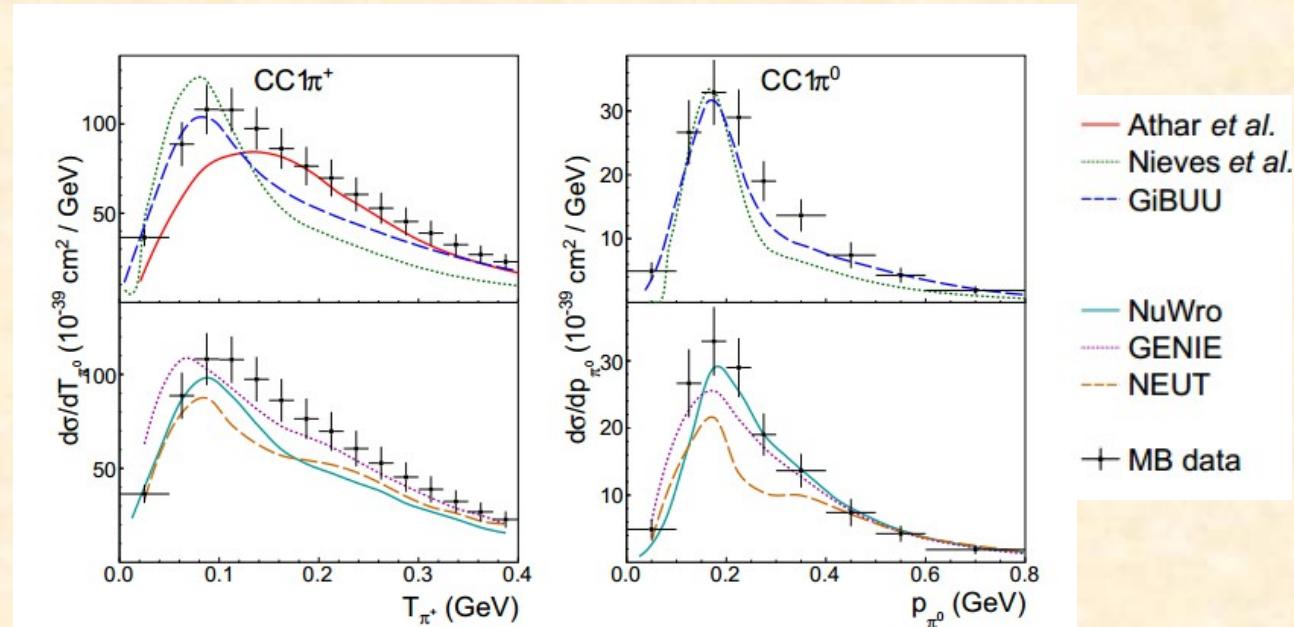
The discrepancy is now understood (Wilkinson, PRD 90 (2014) 112017)



Previous measurements using neutrinos

- Recent measurements done on nuclear targets (K2K, MiniBooNE, SciBooNE, and MINERvA)
 - Hard to disentangle nuclear effects
- Theoretical calculations and event generators are unable to reproduce the measured cross sections

Same MiniBooNE
data top and bottom

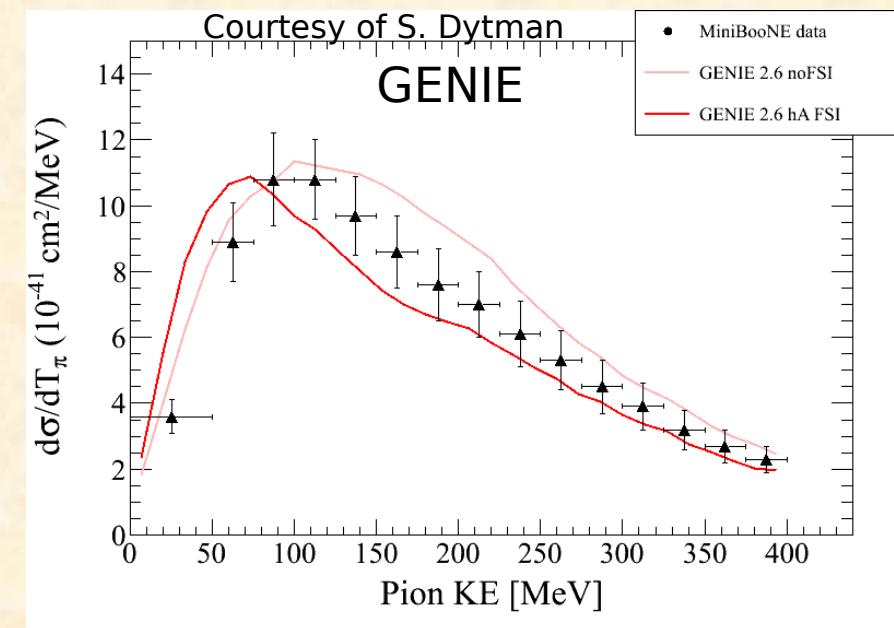
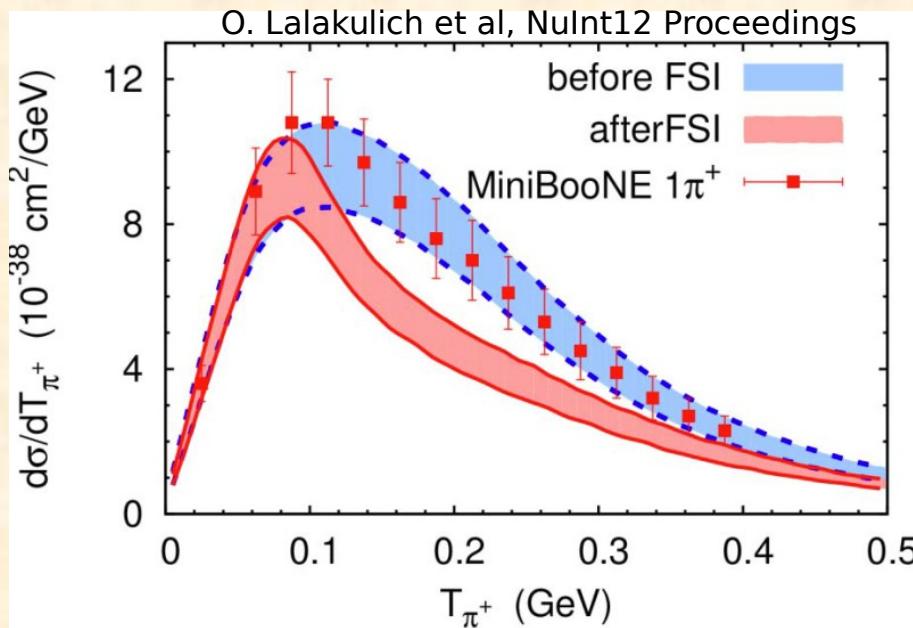


Rodrigues, arXiv:1402.4709



Previous measurements using neutrinos

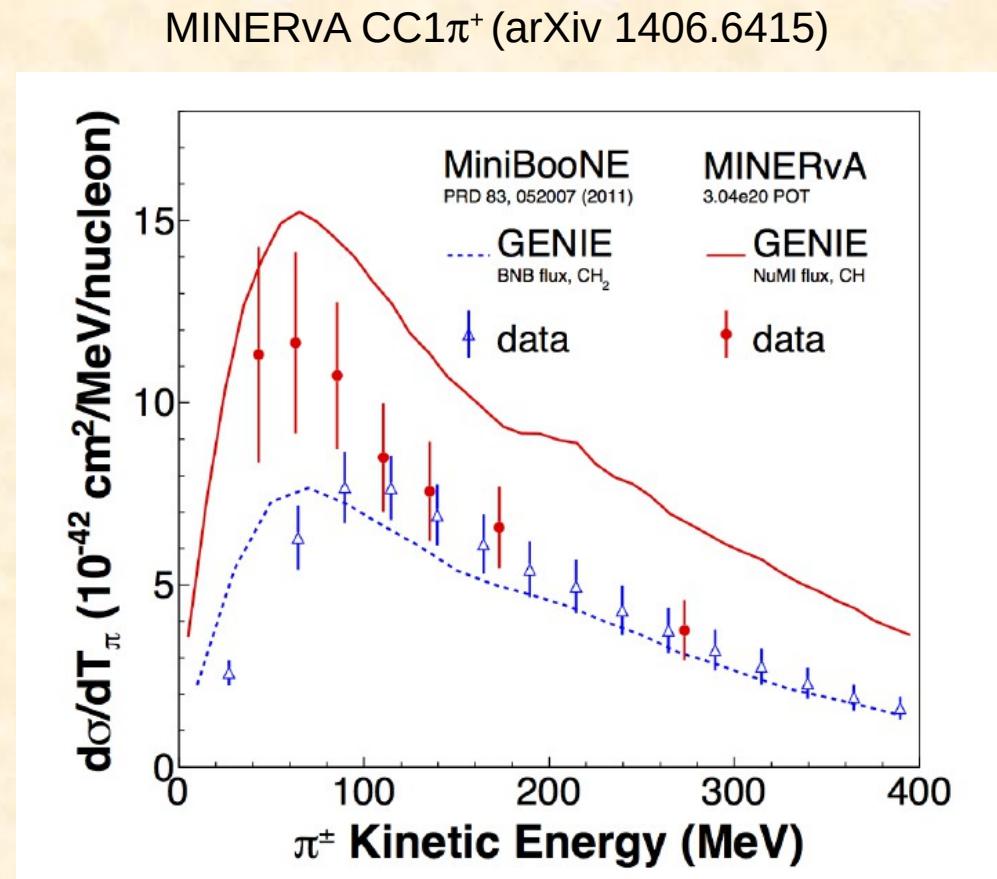
- Recent measurements done on nuclear targets (K2K, MiniBooNE, SciBooNE, and MINERvA)
 - Hard to disentangle nuclear effects
- MiniBooNE is consistent with GiBUU calculation without final state interactions and consistent with both GENIE predictions





MINERvA vs MiniBooNE CC1 π^+

- ◆ Different ν energies (0.6 vs 3.5 GeV)
- ◆ But same Δ mechanism
- ◆ Discrepancies
 - GENIE: MINERvA cross section should be about twice MiniBooNE, but they are roughly equal above 150 MeV
 - GENIE: distributions peak around 60 MeV, true for MINERvA, but not for MiniBooNE





Cross sections and oscillation analyses

- ◆ In T2K oscillation analysis: fit NEUT predictions to MB CC1 π^+ , CC1 π^0 , and NC1 π^0 cross sections simultaneously
- ◆ NEUT and MiniBooNE don't agree
 - Large uncertainties on the parameters that go into the oscillation analysis

NEUT parameters tuned to MB data

Parameter	Input Value	Uncertainty
M_A^{QE} (GeV)	1.21	0.43
x_1^{QE}	1.00	0.11
x_2^{QE}	1.00	0.30
x_3^{QE}	1.00	0.30
x_{SF}	0.0	1.0
$p_F(^{12}\text{C})$ (MeV/c)	217	30
$p_F(^{16}\text{O})$ (MeV/c)	225	30
M_A^{RES} (GeV)	1.16	0.11
$x_1^{CC1\pi}$	1.63	0.43
$x_2^{CC1\pi}$	1.00	0.40
$x^{NC1\pi^0}$	1.19	0.43
$x_{1\pi E_\nu}$	off	on
W_{eff}	1.0	0.51
$x_{\pi-less}$	0.2	0.2
$x^{CCcoh.}$	1.0	1.0
$x^{NCcoh.}$	1.0	0.3
$x^{NCother}$	1.0	0.3
$x_{CCother}$ (GeV)	0.0	0.4
x_{ν_e/ν_μ}	1.0	0.03

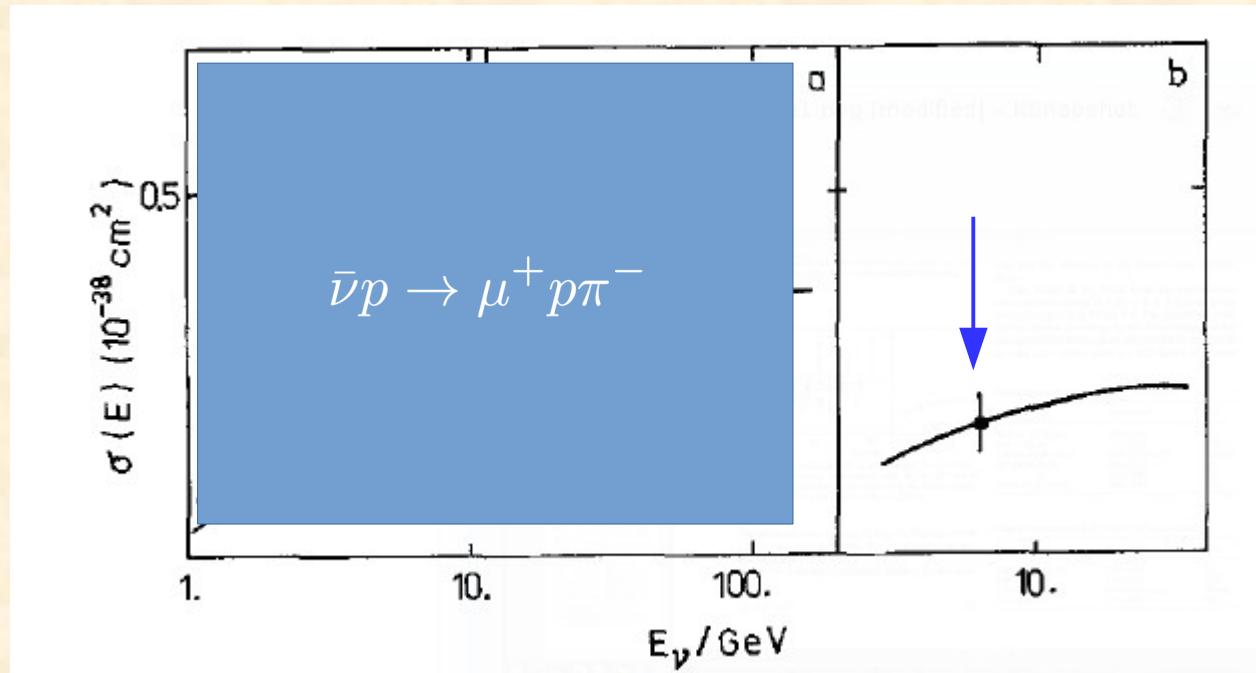
T2K, PRD 88 (2013) 3, 032002



Previous measurements using anti-neutrinos

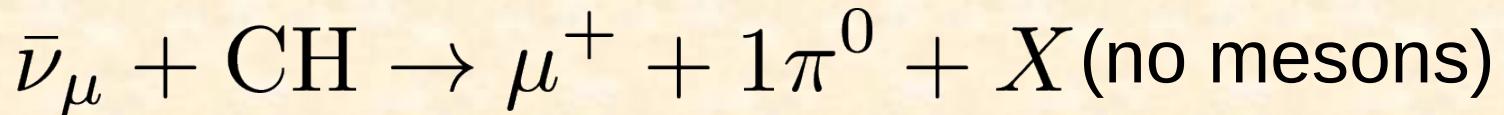
- ◆ There is little previous data on the channel $\bar{\nu}_\mu p \rightarrow \mu^+ n \pi^0$

Single data point from SKAT experiment on CF_3Br (Z. Phys. C 41 (1989) 527)

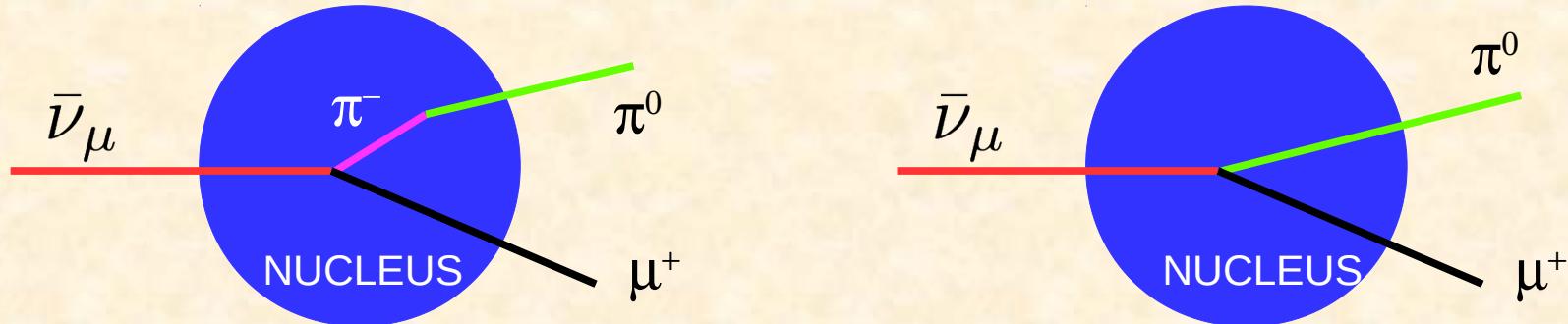




Signal definition



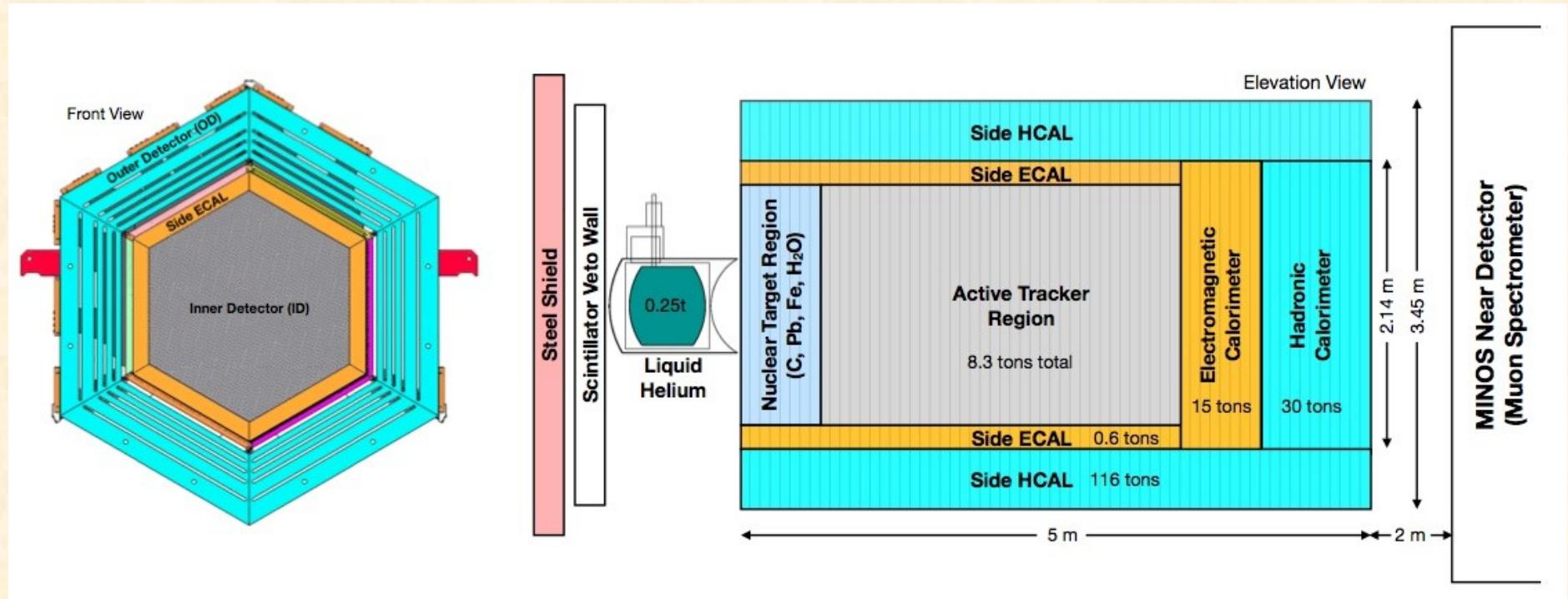
- ◆ μ^+ and π^0 are particles exiting the nucleus. Examples:



- ◆ Alternatively, the signal can be defined using particles from the primary interaction inside the nucleus
 - Require corrections using generator
 - Harder to compare the results with other generators or theoretical models



MINERvA detector

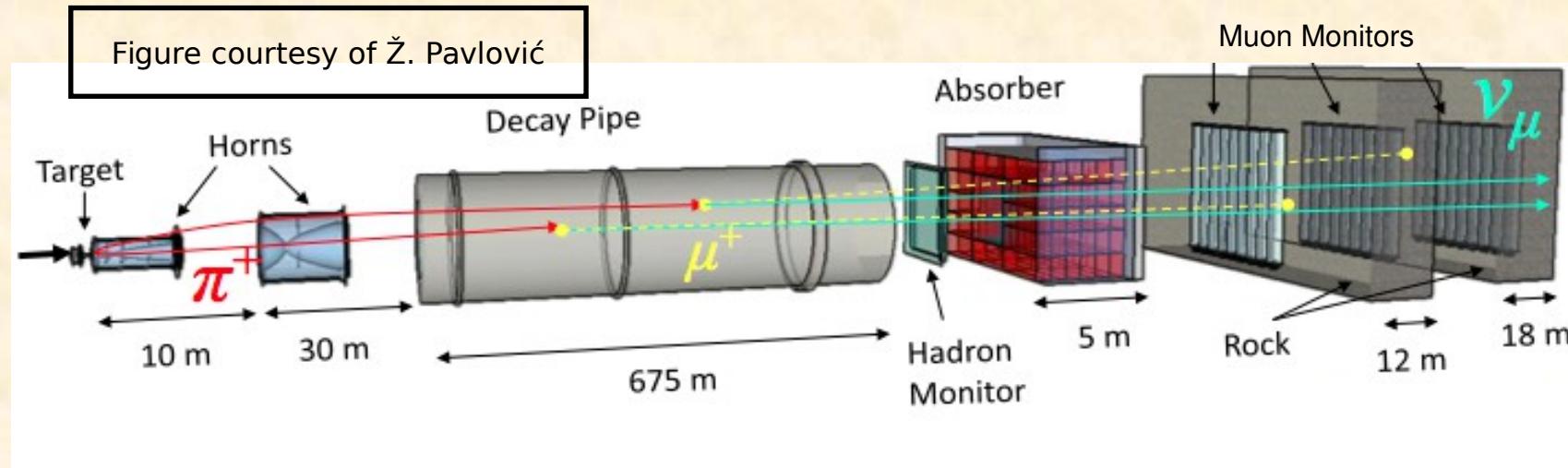


- Fine-grained tracking calorimeter
- 1.7 x 3.34 cm triangular strip
- 32k channels

MINERvA, NIM A 743 (2013) 130



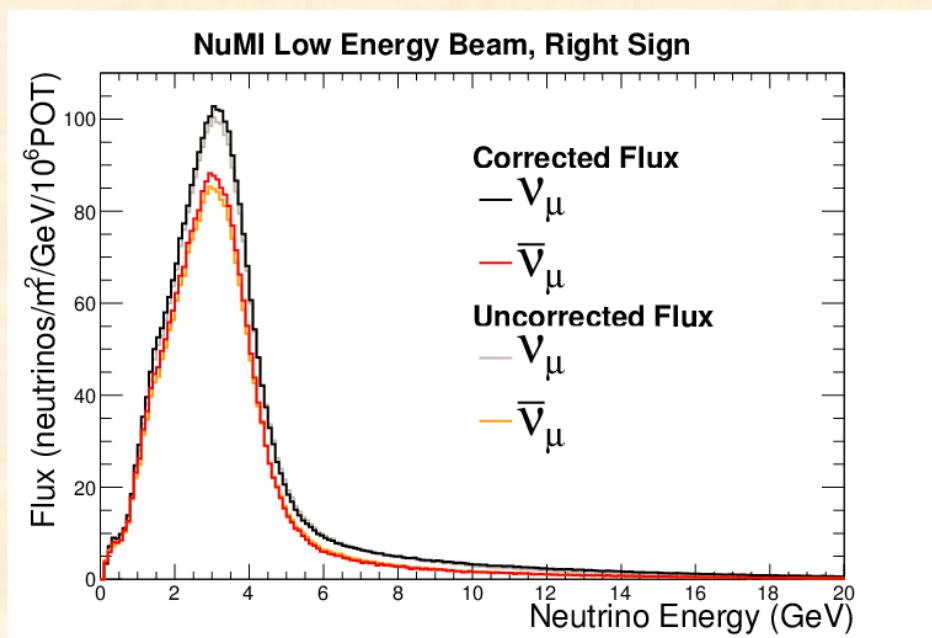
Low-energy NuMI beamline



- 120 GeV protons from Main Injector
- Graphite target
- Neutrino and antineutrino modes



MINERvA flux constraint



- ◆ Hadron production tuning uses NA49 (Eur. Phys. J. C49 (2007) 897) and MIPP π/K ratio data (Fermilab thesis 2007-61)
- ◆ Use difference between models as uncertainties where there is no data point
- ◆ $\sim 10\%$ systematic uncertainty at the focusing peak
- ◆ Future plans
 - $\nu_\mu + e^-$ scattering
 - Special runs
 - Recent MIPP data

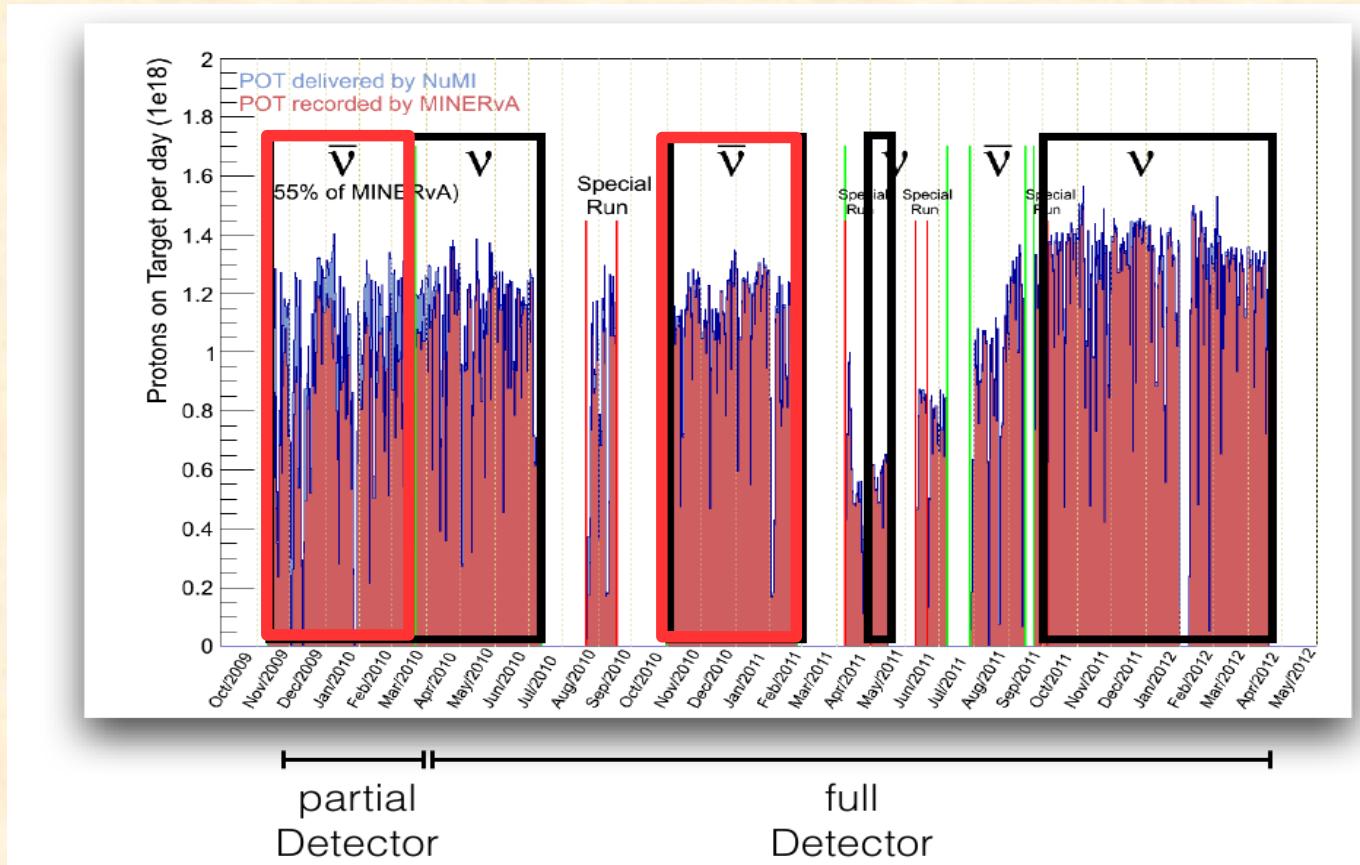


Neutrino event generator

- ◆ Use GENIE 2.6.2
- ◆ Rein-Sehgal model for baryon resonance production
- ◆ Full intra-nuclear cascade is represented by a single hadron-nucleus interaction tuned to beam pion data for final state interactions



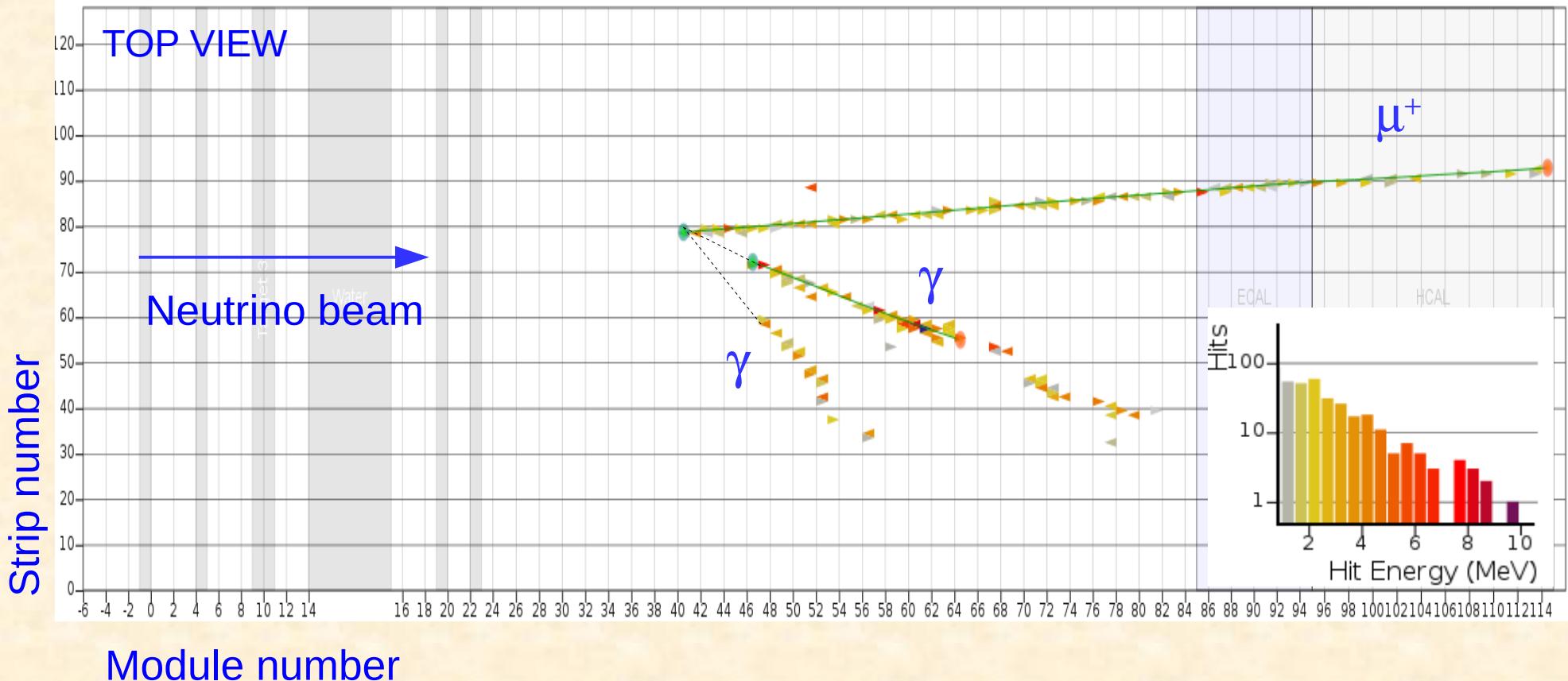
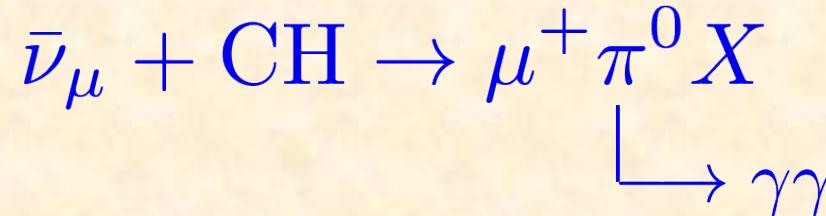
Datasets



- ◆ There are 2.01×10^{20} POT anti-neutrino mode (red boxes).
- ◆ To demonstrate the analysis procedure, I'll use the antineutrino dataset taken with full detector. Final cross sections include both datasets



Candidate signal event





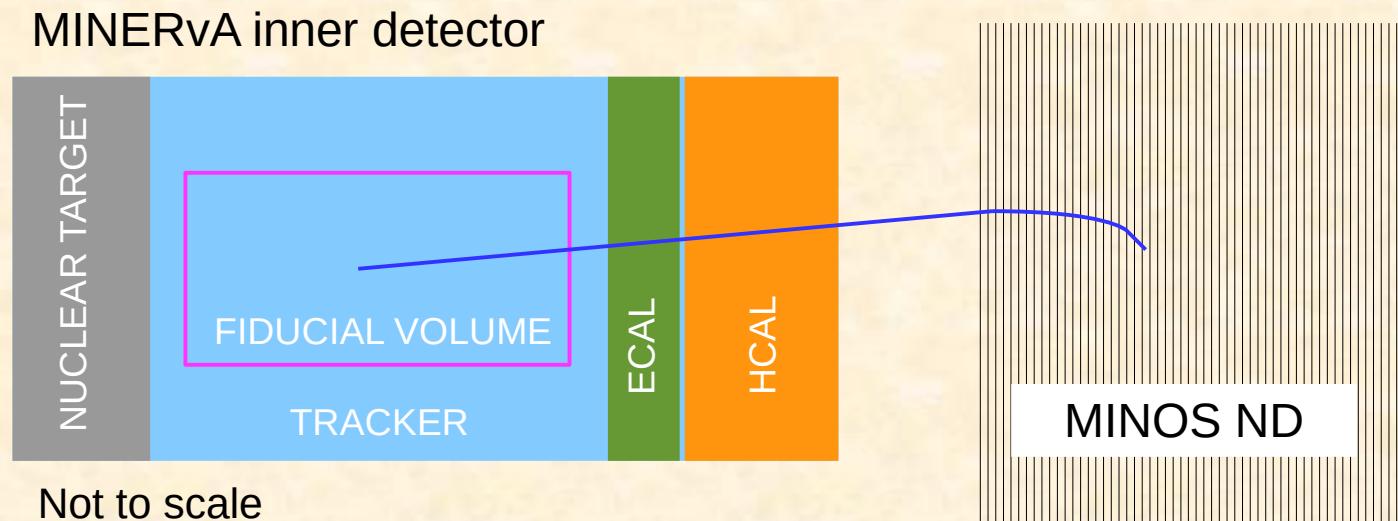
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Event selection and π^0 reconstruction



MINOS-matched μ^+

- ◆ One μ^+ track matched to MINOS near detector
- ◆ Vertex within the fiducial volume

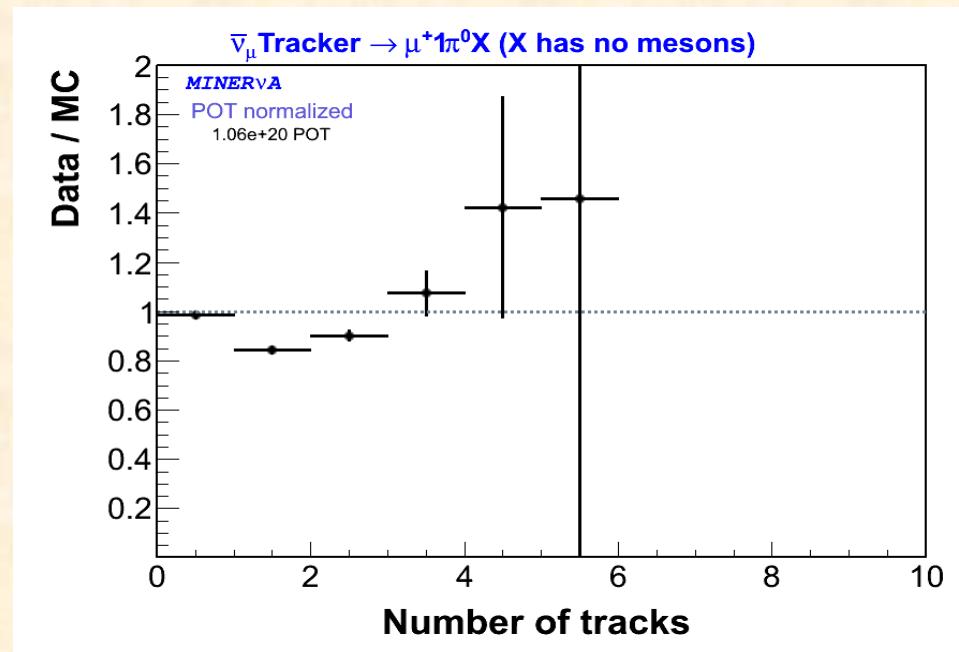
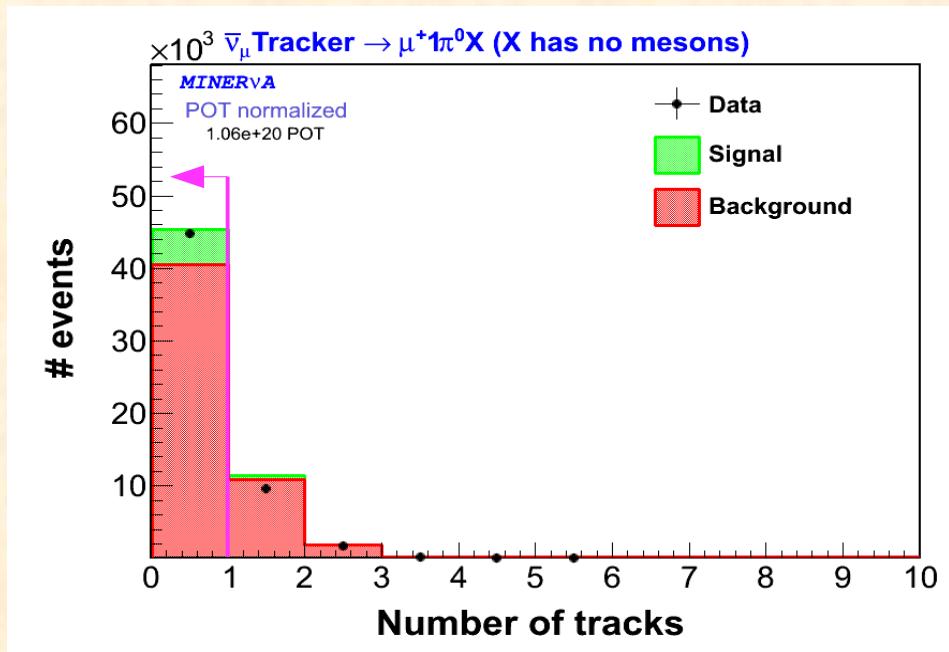




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Number of non-muon tracks at the primary vertex

Require that μ^+ is the only track at the primary vertex

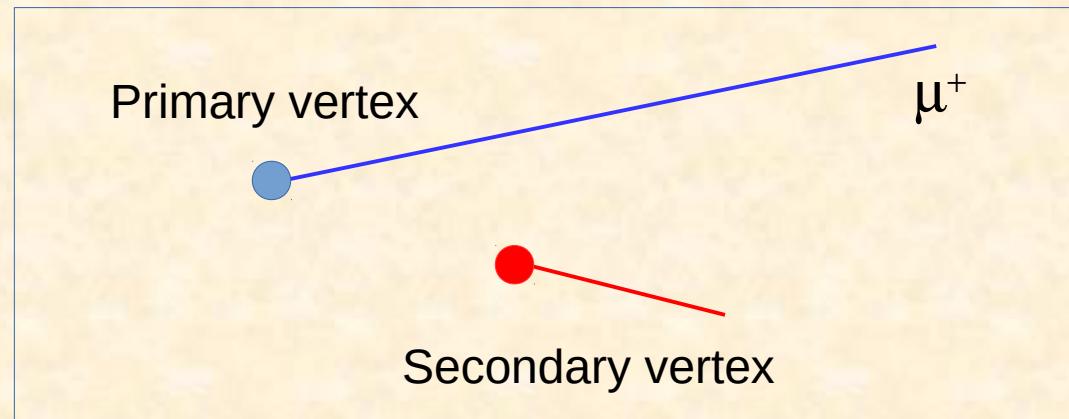
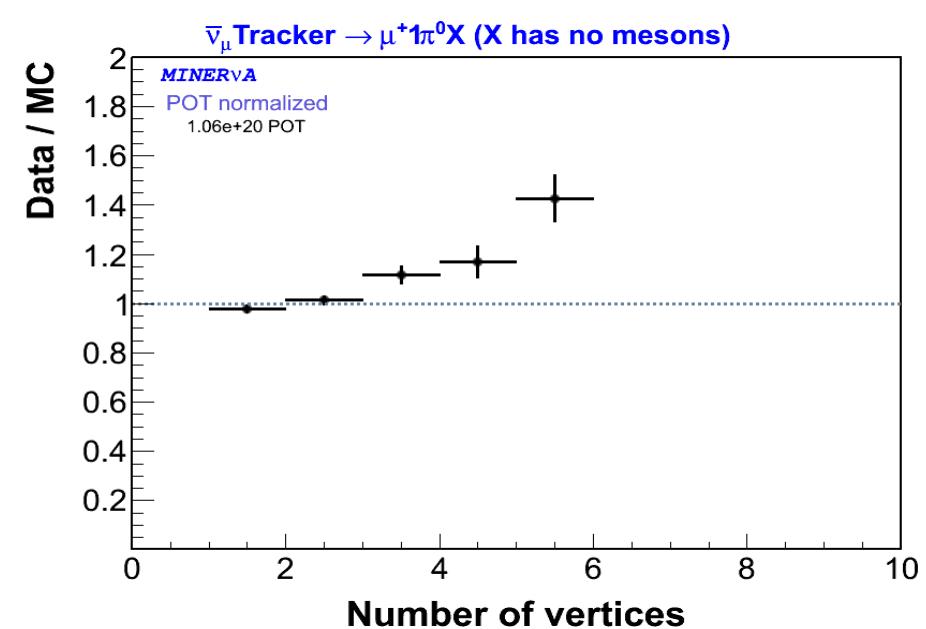
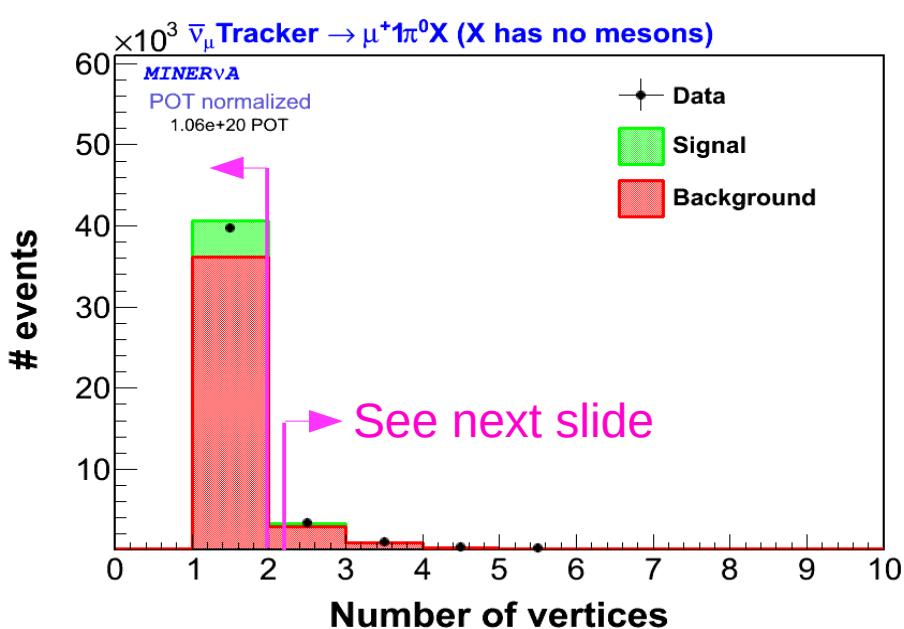


A small fraction of signal events are rejected due to either:

- 1) final state proton energetic enough to be tracked
- 2) one of the photons converts within 5 cm of the vertex and is tracked



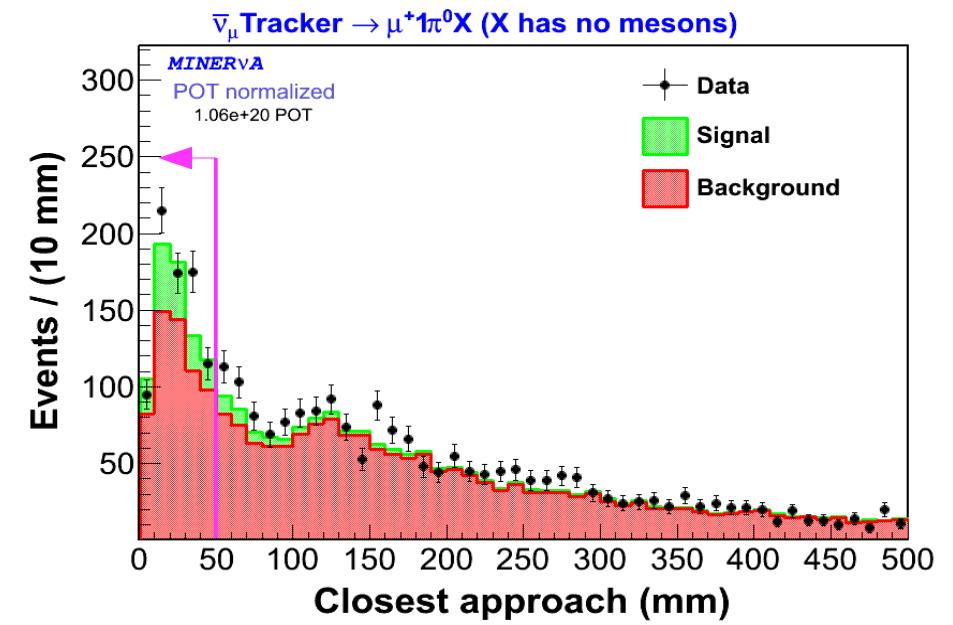
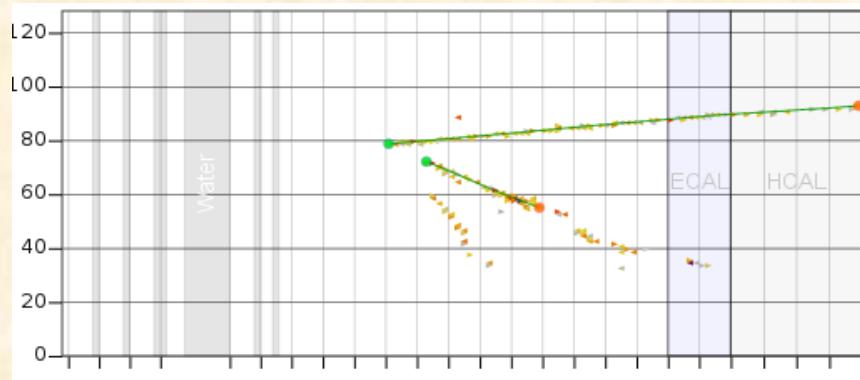
Number of vertices





Tracks at secondary vertices

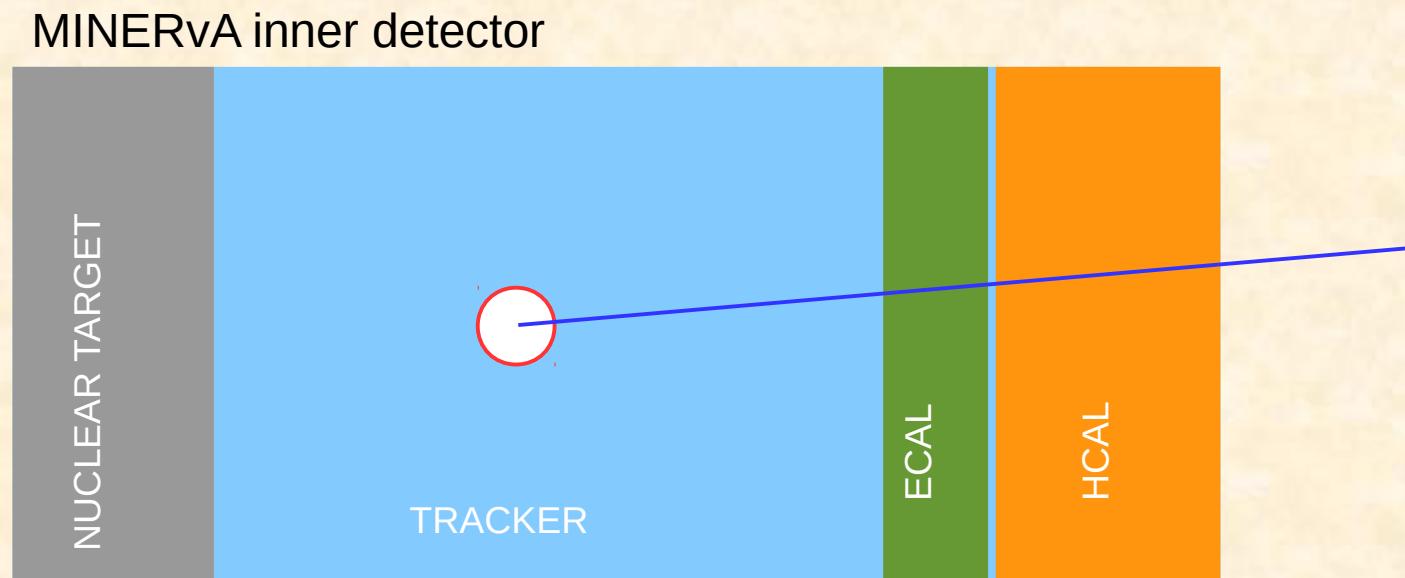
Photons from π^0 decay can also produce (one-track) secondary vertex, keep the event if the track points back to the vertex





Vertex energy

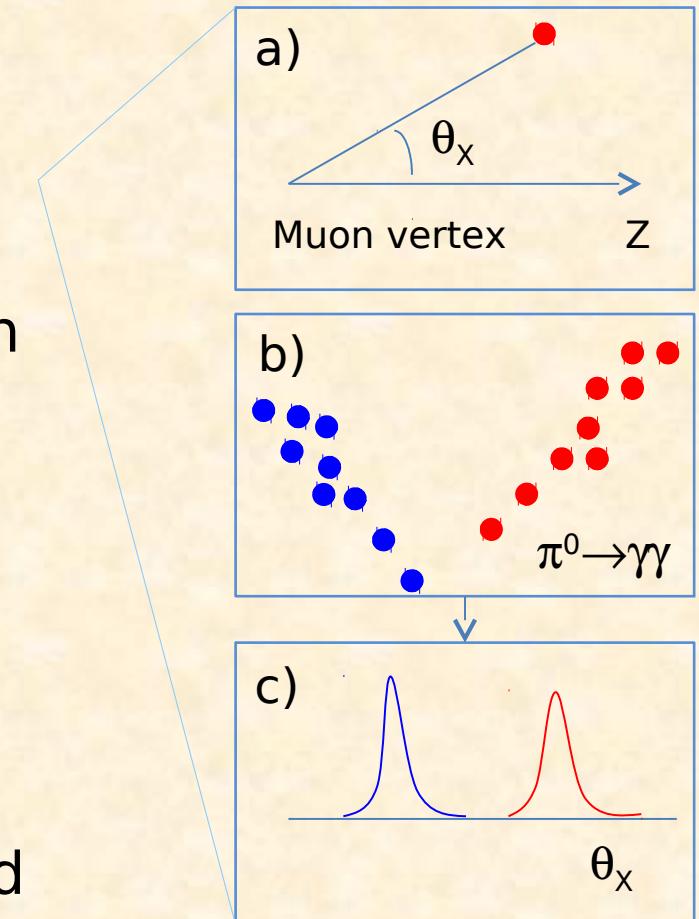
- ◆ Hits within 9 cm radius from the vertex are not used in the π^0 reconstruction





π^0 reconstruction algorithm

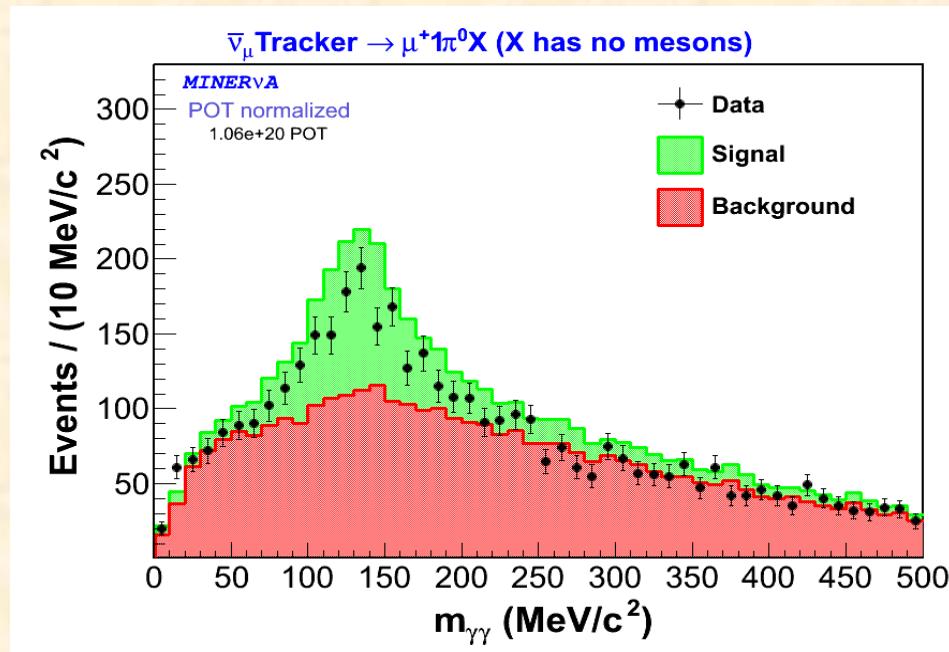
- 1) In the X view, make an angular distribution of hits around the vertex, then search for peaks in this distribution
- 2) For each peak, search for hits in the U,V views satisfying stereo condition
- 3) Fit hits associated with each θ_x peak to determine photon three dimensional direction
- 4) Photon energies are determined by calorimetry





Two-photon invariant mass

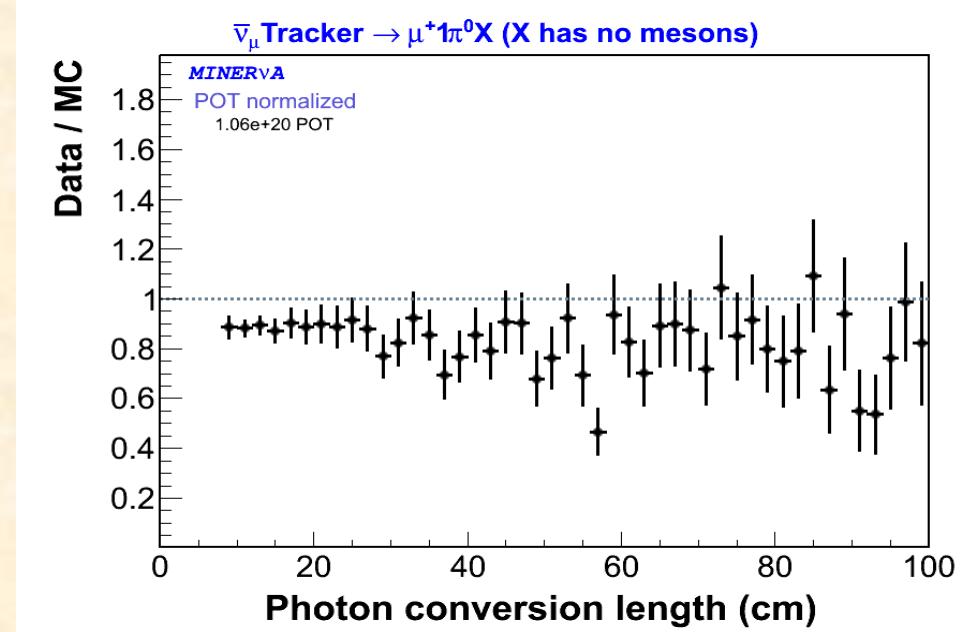
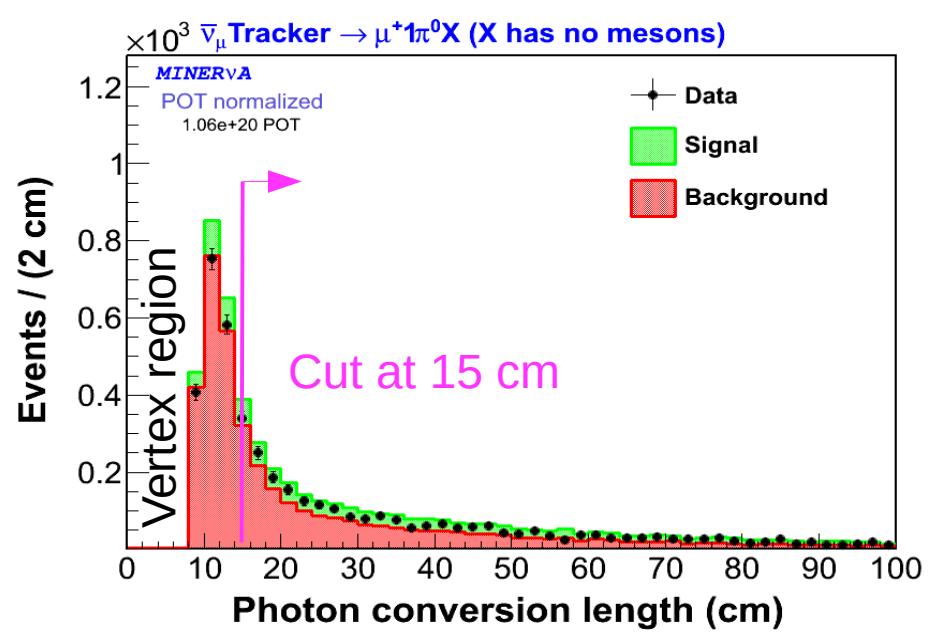
$$m_{\gamma\gamma}^2 = 2E_1E_2(1 - \cos\theta_{\gamma\gamma})$$





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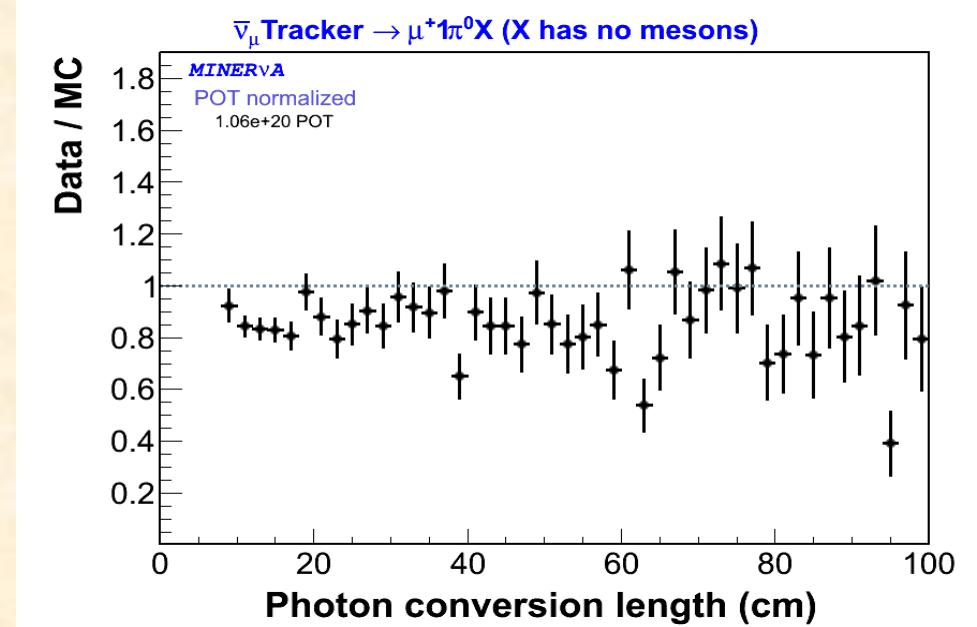
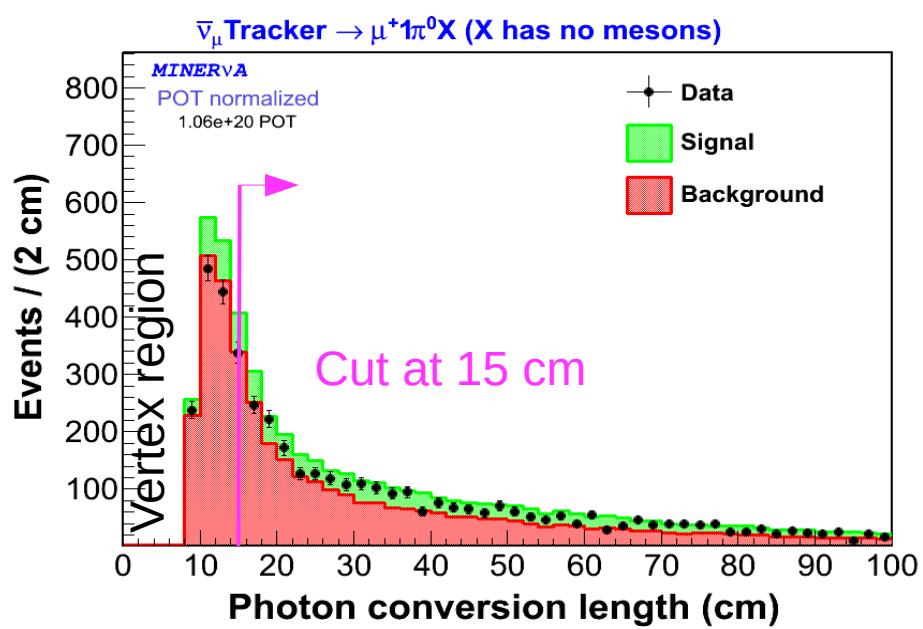
Photon conversion length ($\gamma 1$)





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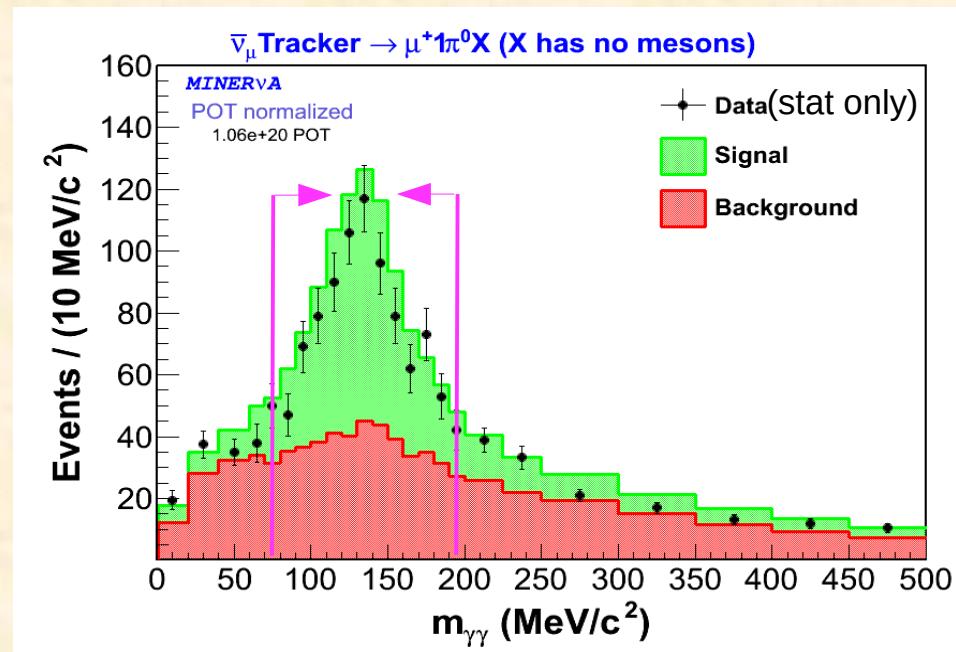
Photon conversion length (γ^2)





Two-photon invariant mass

$$m_{\gamma\gamma}^2 = 2E_1E_2(1 - \cos\theta_{\gamma\gamma})$$



Mass cut:
 $75 < m_{\gamma\gamma} < 195$ MeV/c²

Signal events on the tail are due to candidate photons reconstructed from neutron energy depositions

After the mass cut, the sample consists of 55% signal and 45% background events. Data have 926 events (plus 437 events from the partial detector)



Neutrino energy

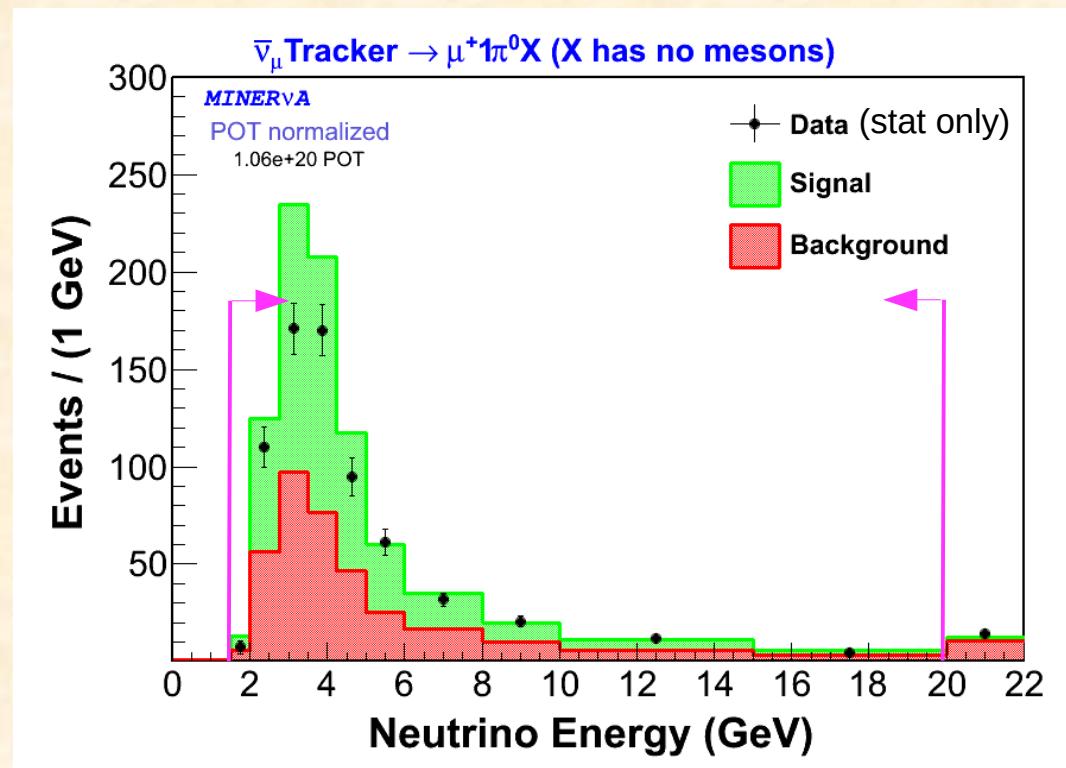
$$T_n = \frac{1}{2} \frac{((E_\mu - p_{\mu L}) + (E_\pi - p_{\pi L}))^2 + (\vec{p}_{\mu T} + \vec{p}_{\pi T})^2}{m_N - (E_\mu - p_{\mu L}) - (E_\pi - p_{\pi L})}$$

$$E_\nu = E_\mu + E_{\pi^0} + T_n$$

Assume that the π^0 is produced together with a nucleon, e.g., $\Delta^0 \rightarrow n + \pi^0$ and initial nucleon at rest

$$1.5 < E_\nu < 20 \text{ GeV}$$

- Low end cut since we have no efficiency
- High end cut since we don't know the flux well

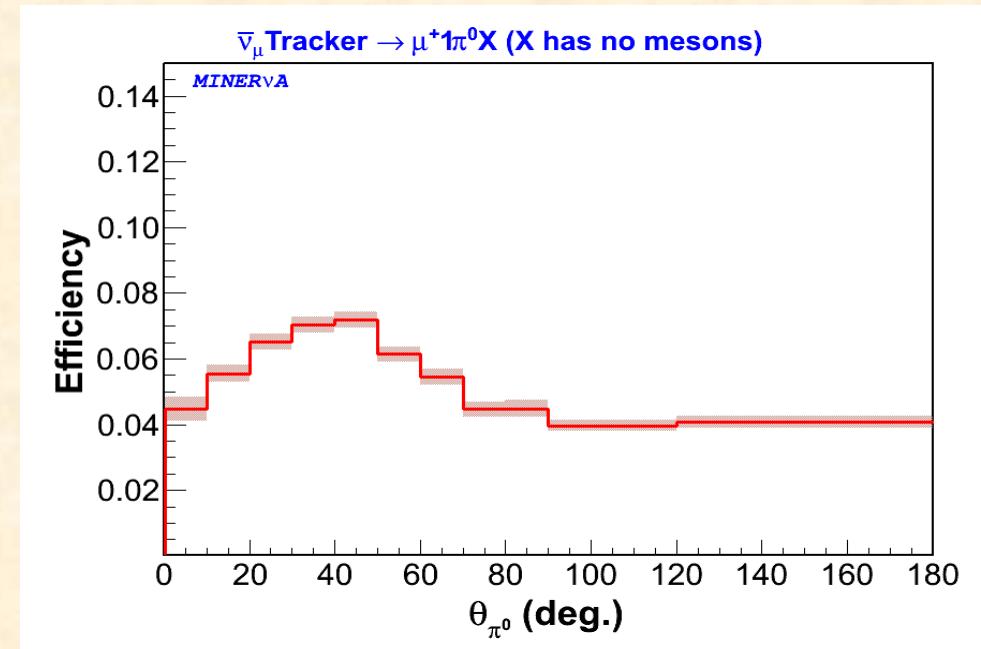
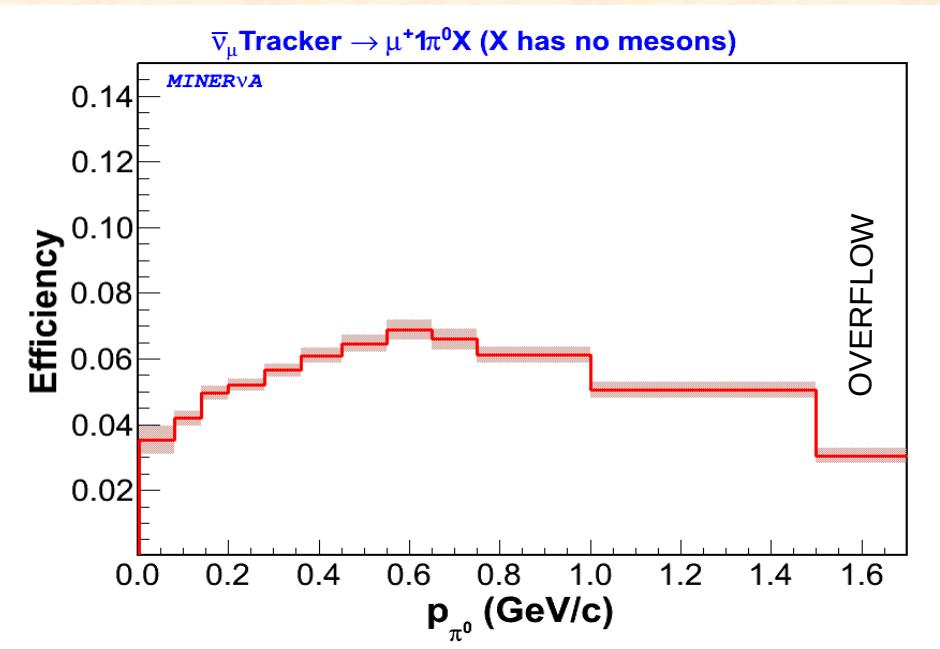




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Efficiency

Efficiency curves from the simulation



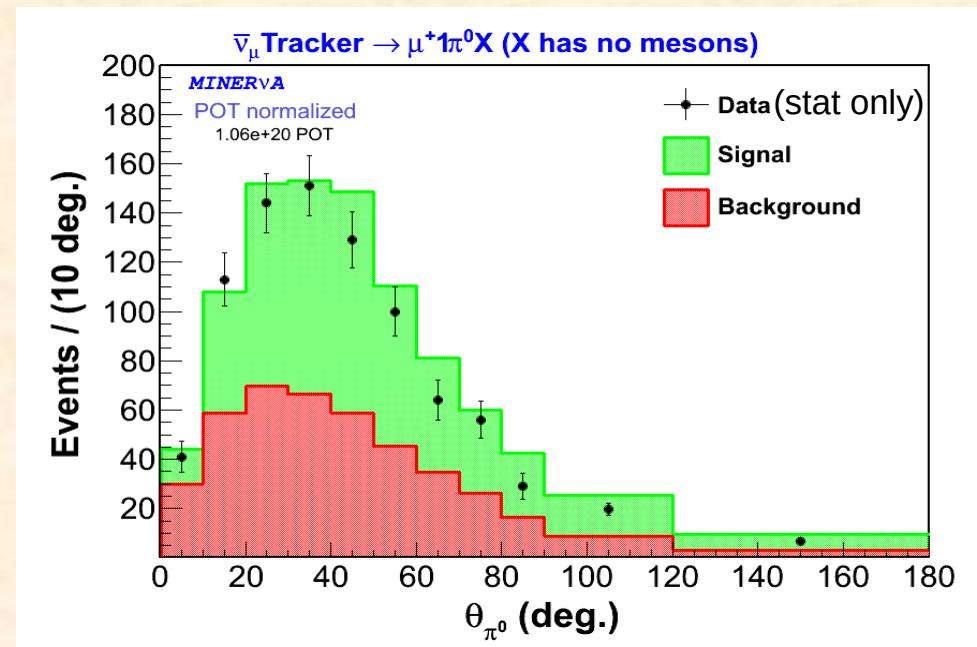
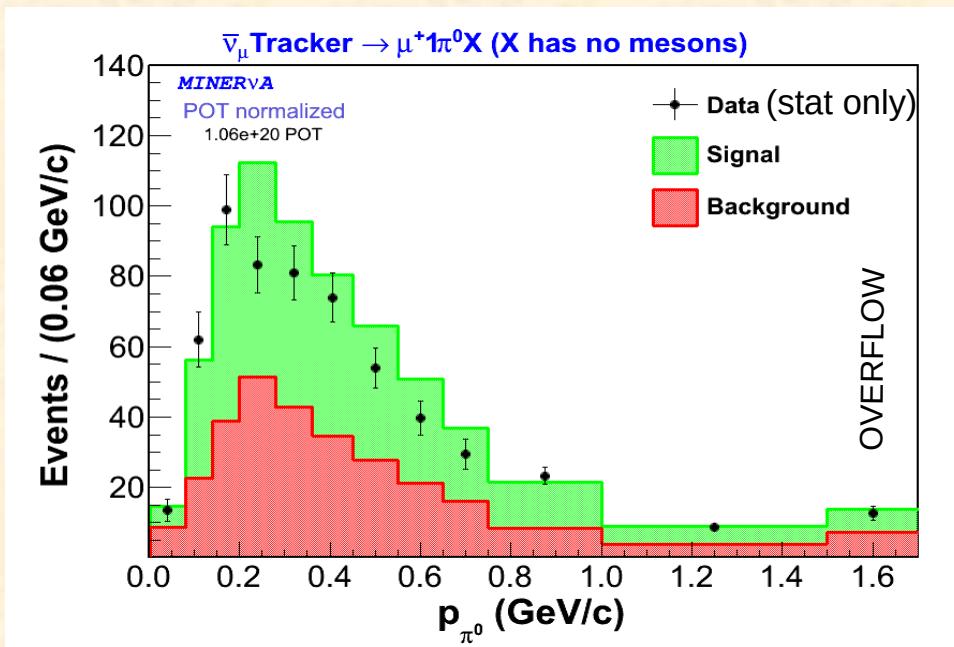


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π^0 momentum and angle

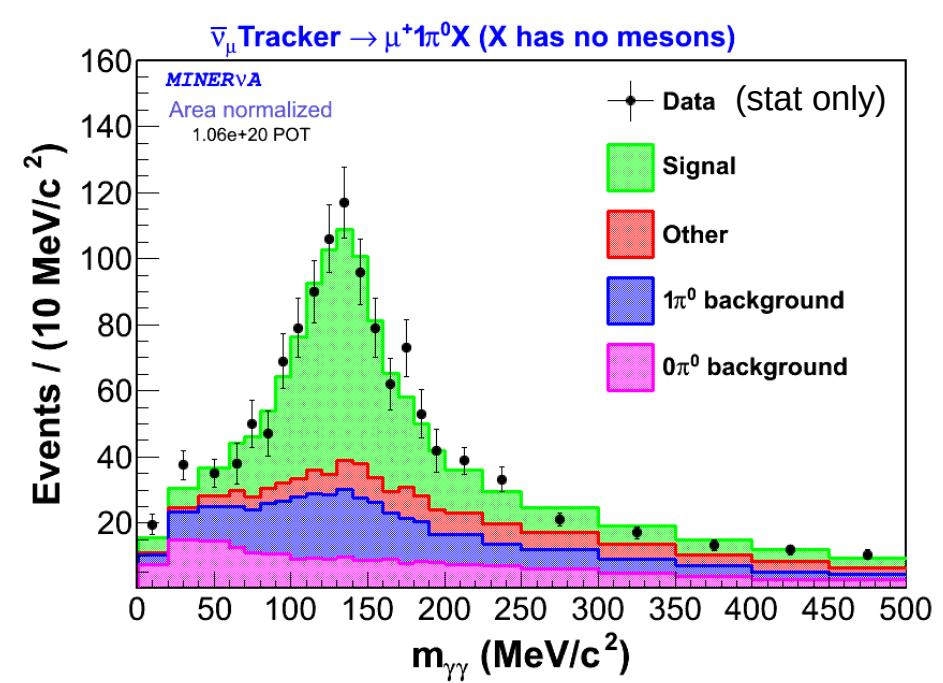
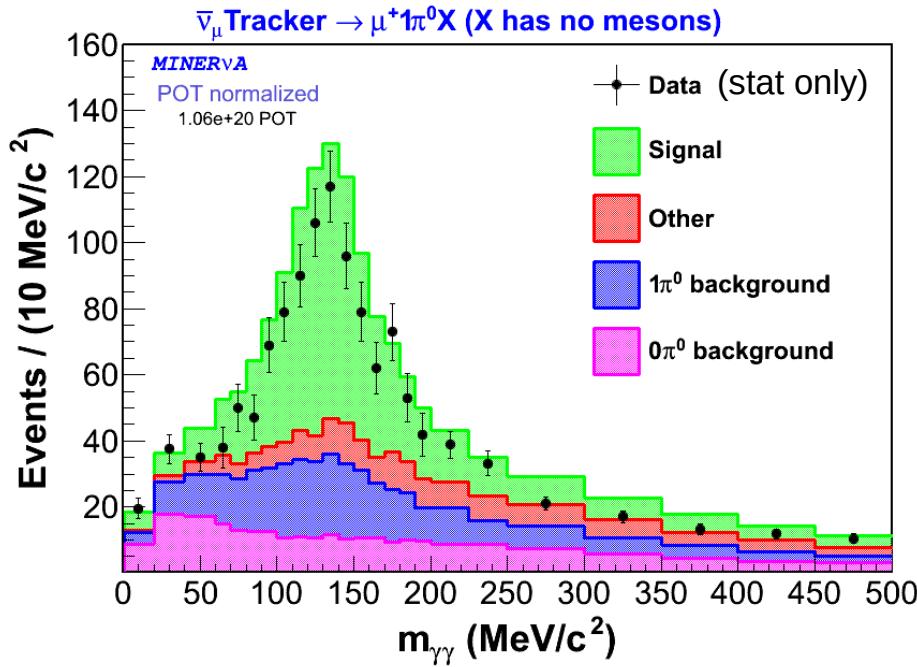
$$\vec{p}_{\pi^0} = \vec{k}_1 + \vec{k}_2$$

Selected sample

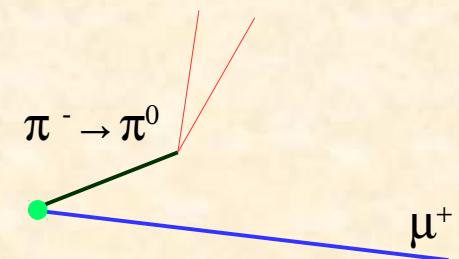




More on backgrounds



- $1\pi^0$ background: 1) $\pi^- \rightarrow \pi^0$ or 2) $\pi^- + \pi^0$ from the interaction nucleus
- $1\pi^0$ background enhancement around the mass peak:
 - 1) $1\pi^0$ reconstruction assumes the π^0 from the vertex
 - 2) π^- confuses the π^0 reconstruction



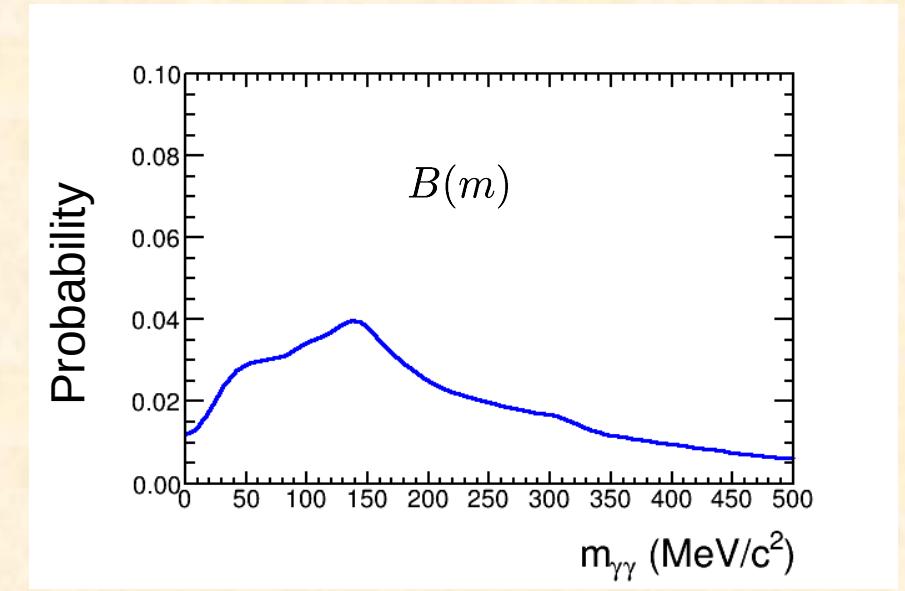
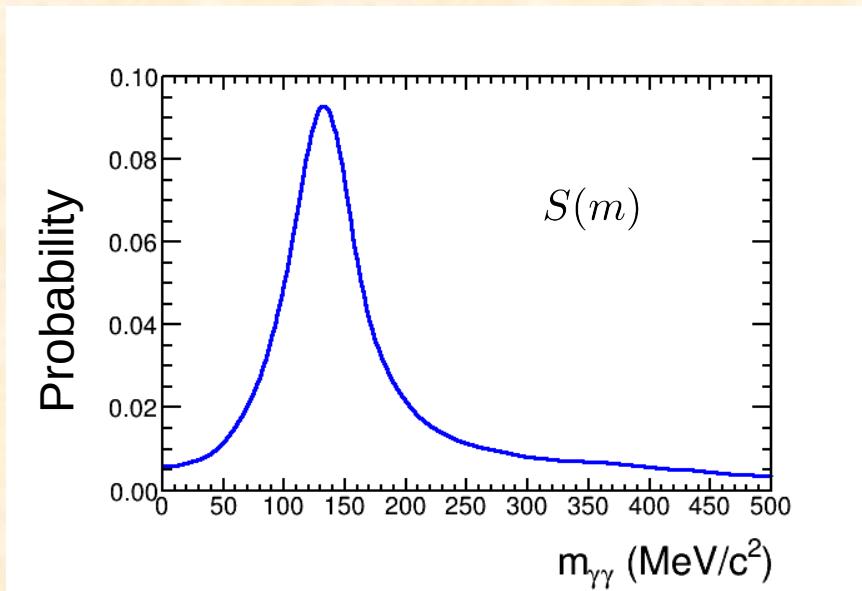


Background prediction constraint

Mass model:

$$M(m) = N_{sig}S(m) + N_{bkg}B(m)$$

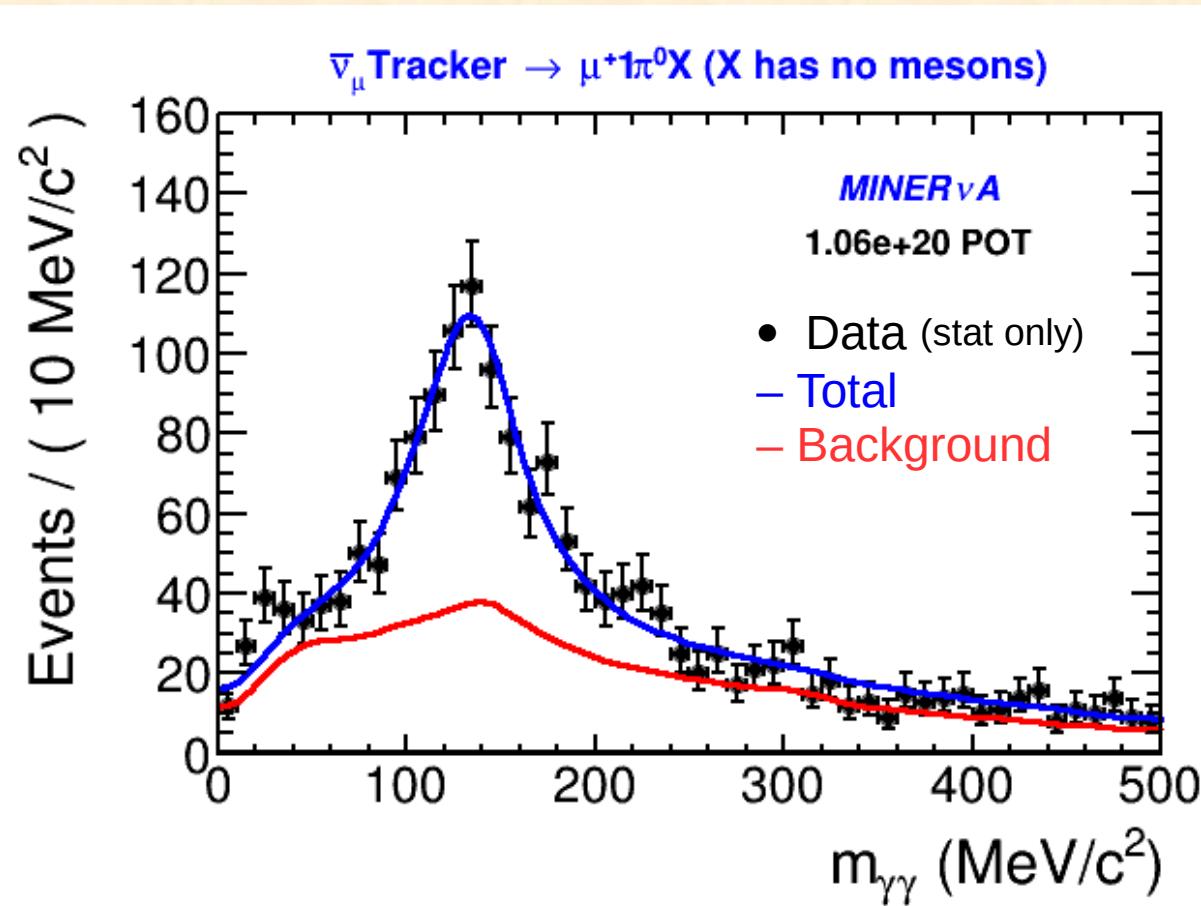
with templates from the simulation





Background prediction constraint

$$M(m) = N_{sig}S(m) + N_{bkg}B(m)$$



$$N_{bkg}(75 < m_{\gamma\gamma} < 195 \text{ MeV}/c^2) = 391.4 \pm 30.0$$



Cross section calculation

Differential cross-section
vs. θ_π

Unfolding function: convert from reconstructed θ_π to true θ_π

background constrained by data

$$\left(\frac{d\sigma}{d\theta}\right)_i = \frac{1}{\Phi_\nu \times T_n} \frac{1}{(\Delta\theta_\pi)_i} \frac{\sum_j U_{ij} (N_j^{data} - N_j^{bkg})}{\epsilon_i}$$

i: true
j: reco

Integrated flux, targets | bin size

Selection efficiency and acceptance

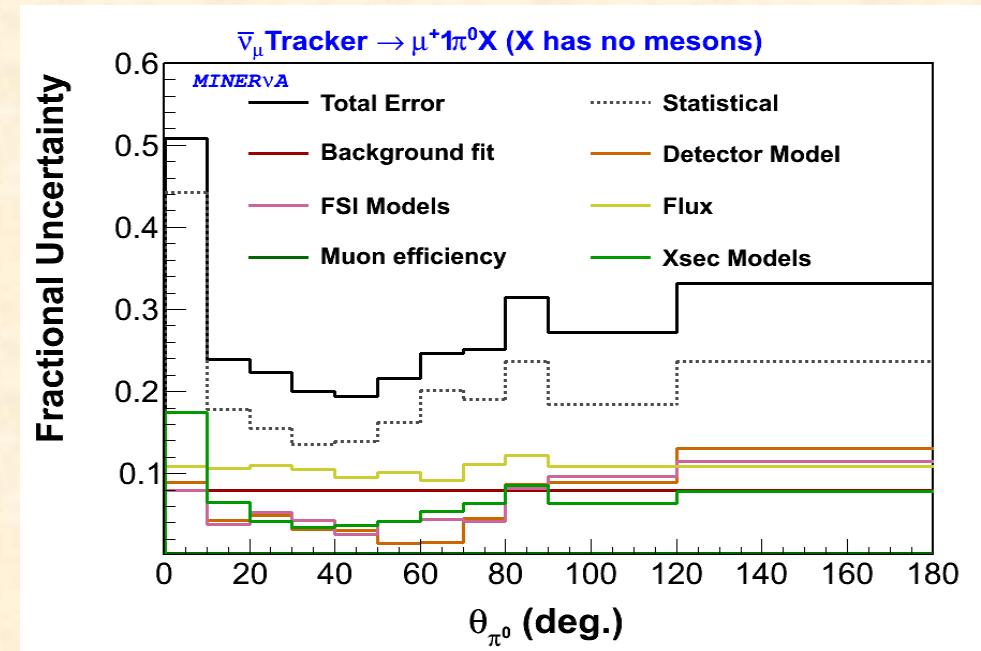
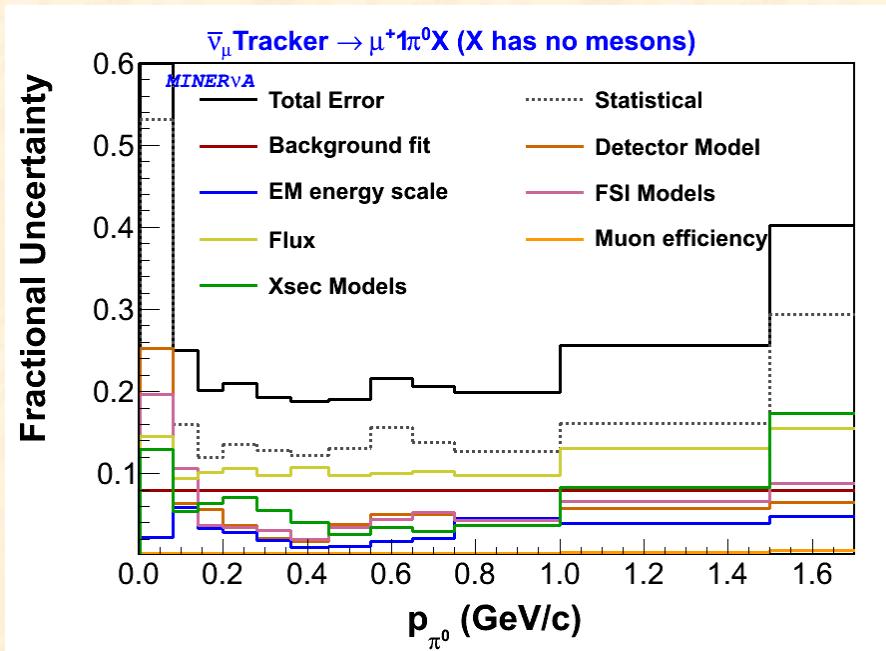
We calculate the cross sections separately for the partial and full detectors. In the following, I'll show the averaged cross sections of the two datasets



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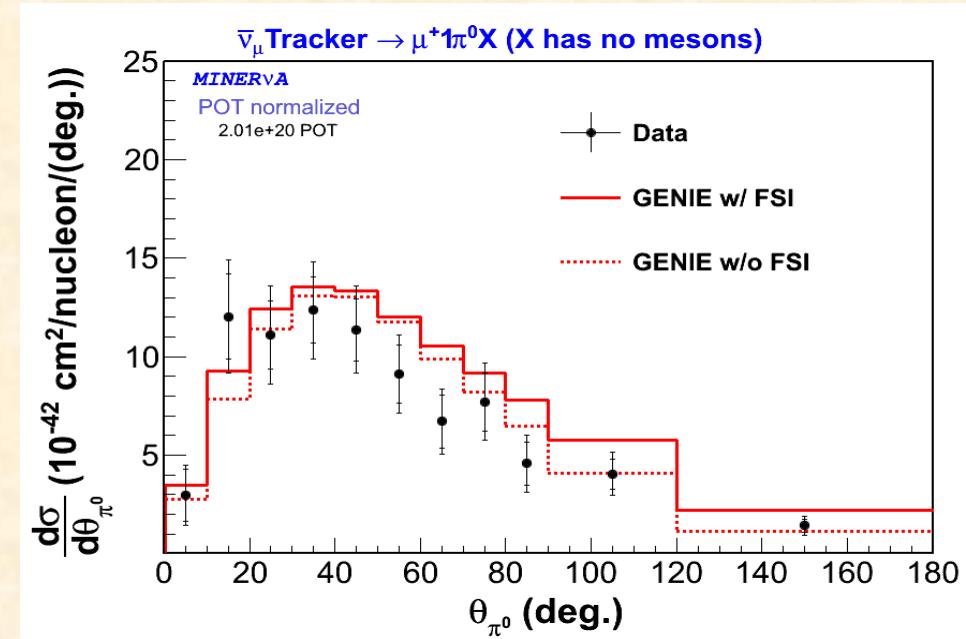
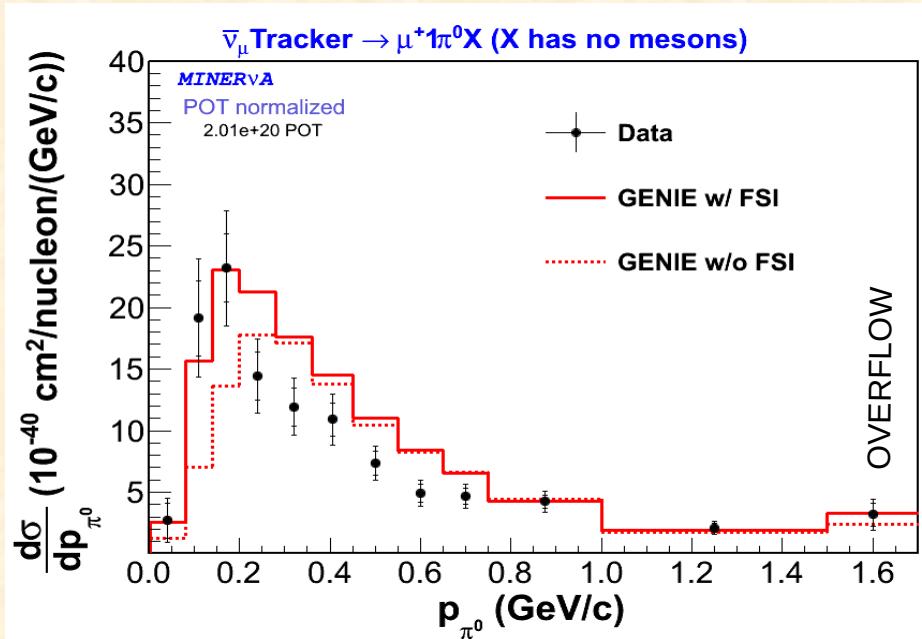
Cross section uncertainty summary

Total uncertainties on the differential cross sections are about 20-30%





Cross sections

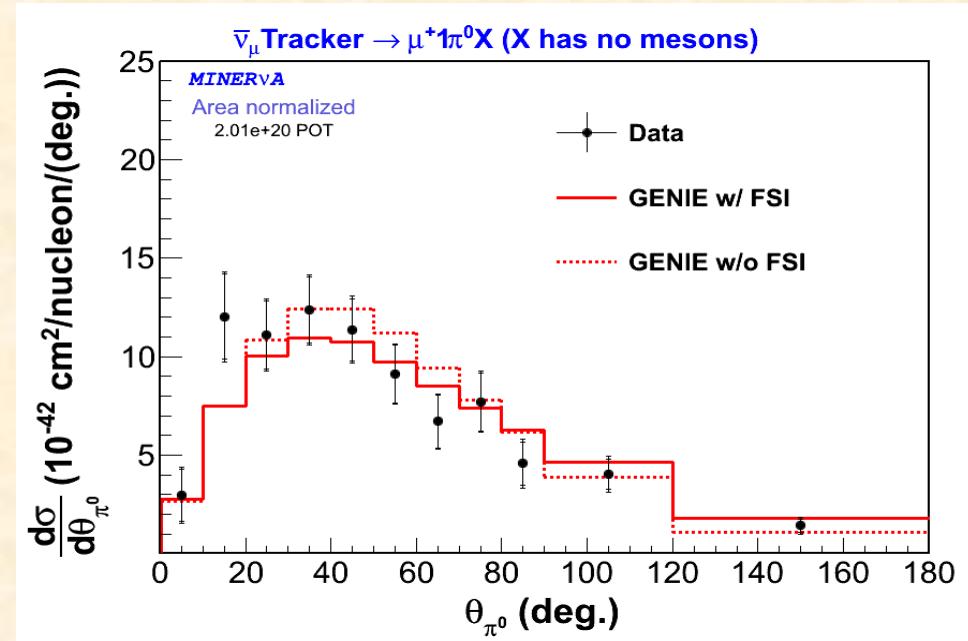
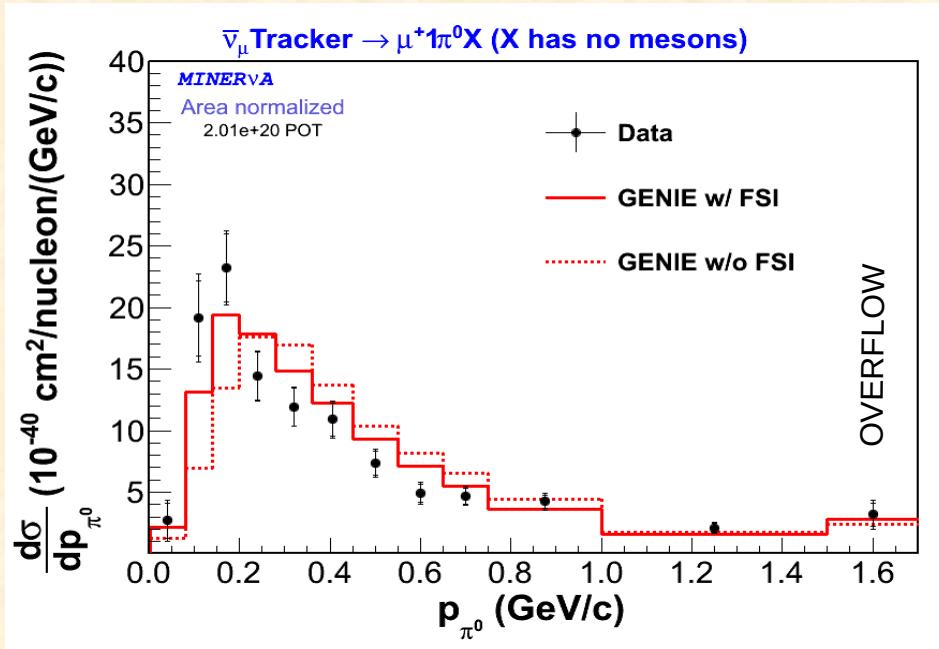


- Data are in better agreement with the cross section with FSI
- Cross section with FSI is above that without FSI across momentum range
- Above 0.3 GeV/c, cross sections with and without FSI are similar
- Below 0.3 GeV/c, cross sections with and without FSI are very different

- FSI produce slightly more both forward and backward going signal



Shape-only cross sections



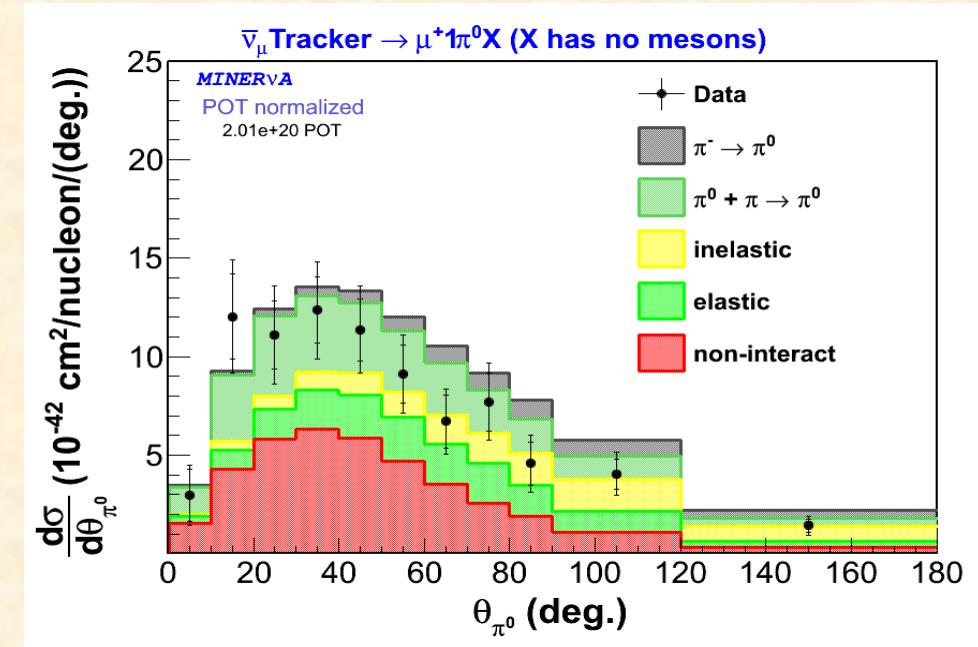
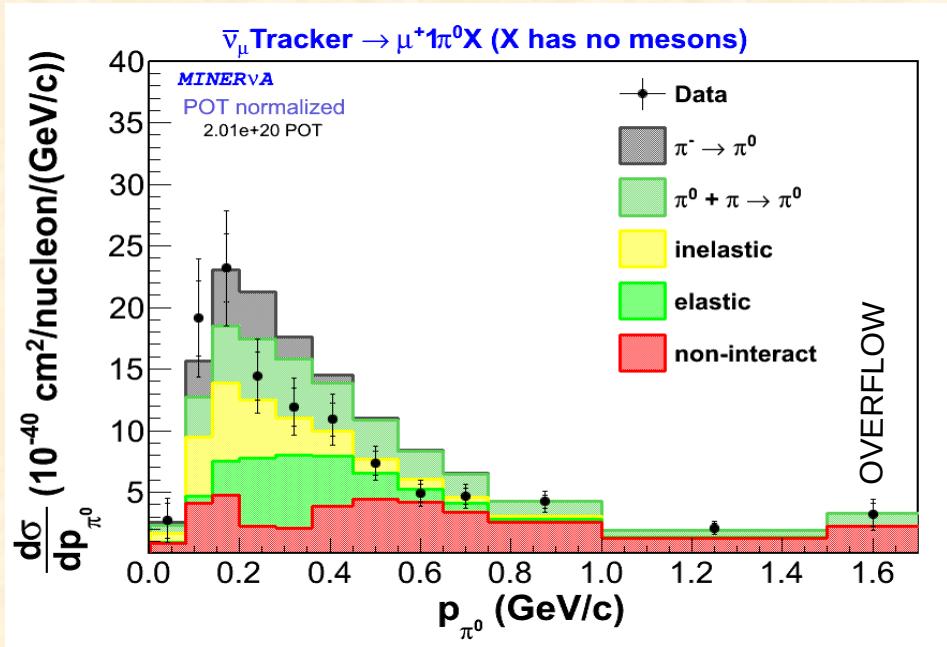
- Again data better agree with cross section with FSI
- Above 0.75 GeV/c data agree with both predictions in rate and shape

- Both predictions have similar shape and agree with data



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Final state interaction (FSI) channels



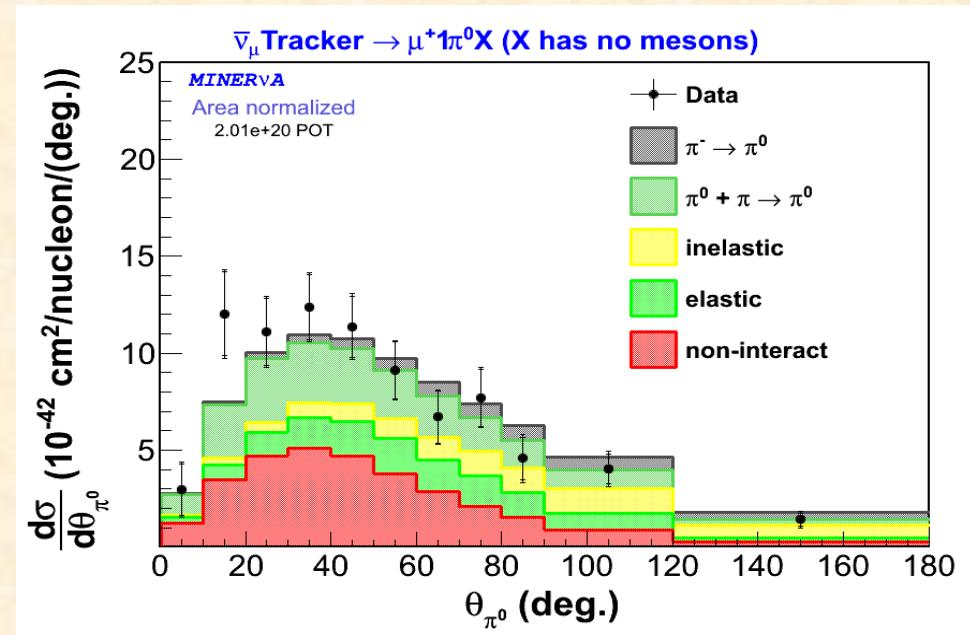
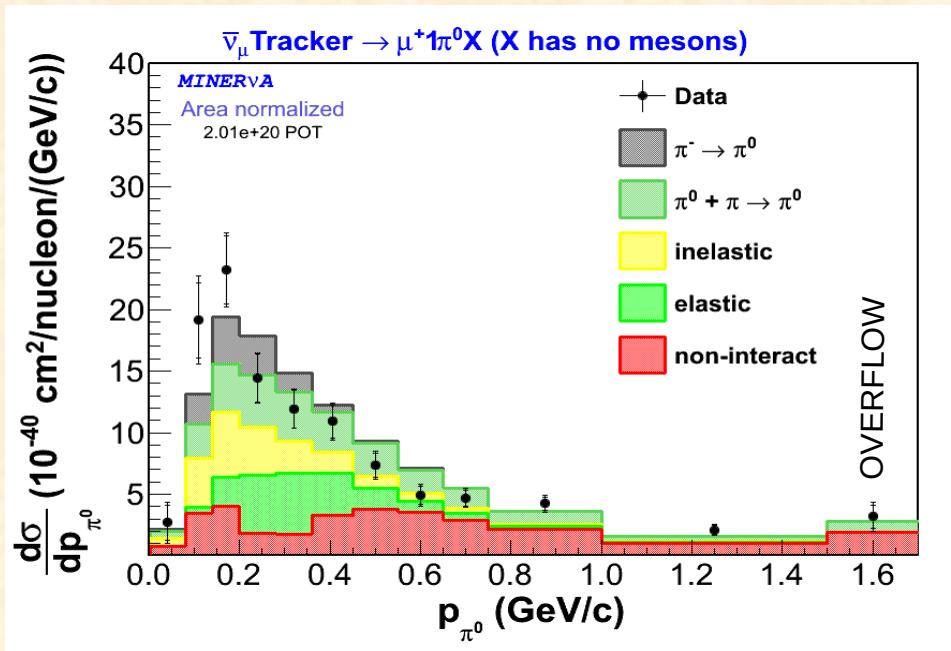
- Generators assume: pions born inside nucleus are similar to beam pions
- Use beam pion data to model FSI
- It is remarkable that generators (GENIE) can reproduce the measured cross sections



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Final state interaction (FSI) channels

Shape-only cross sections



- There are too many π^0 s at high momentum, reduced charge exchange with increased inelastic strength might yield improvement

- There are too many π^0 s at high angle: scattering angle assigned to these processes are too large

Tune neutrino generator using neutrino-nucleus data, an improvement from beam pion data



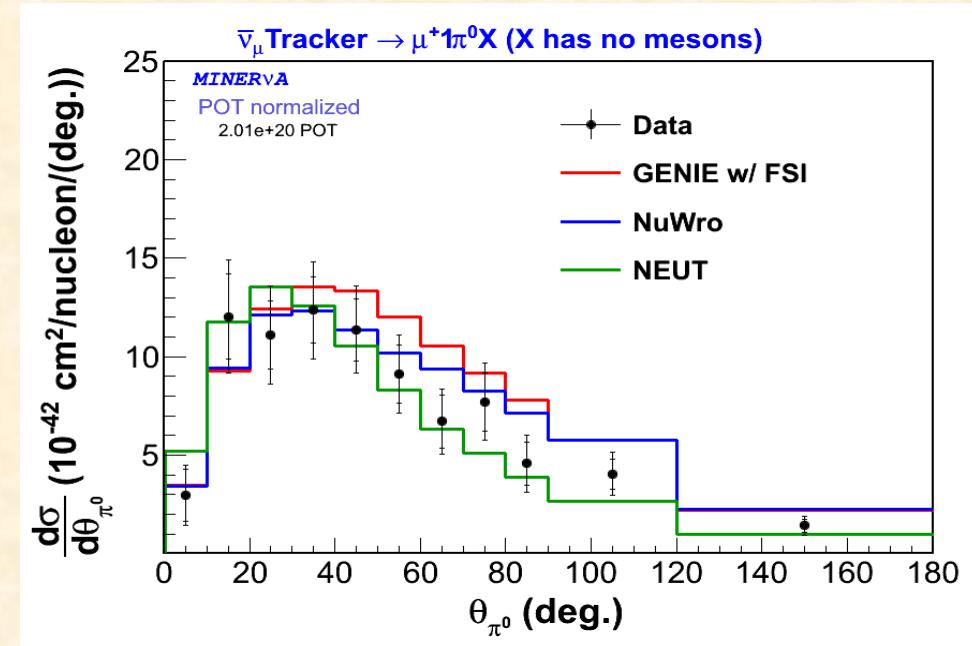
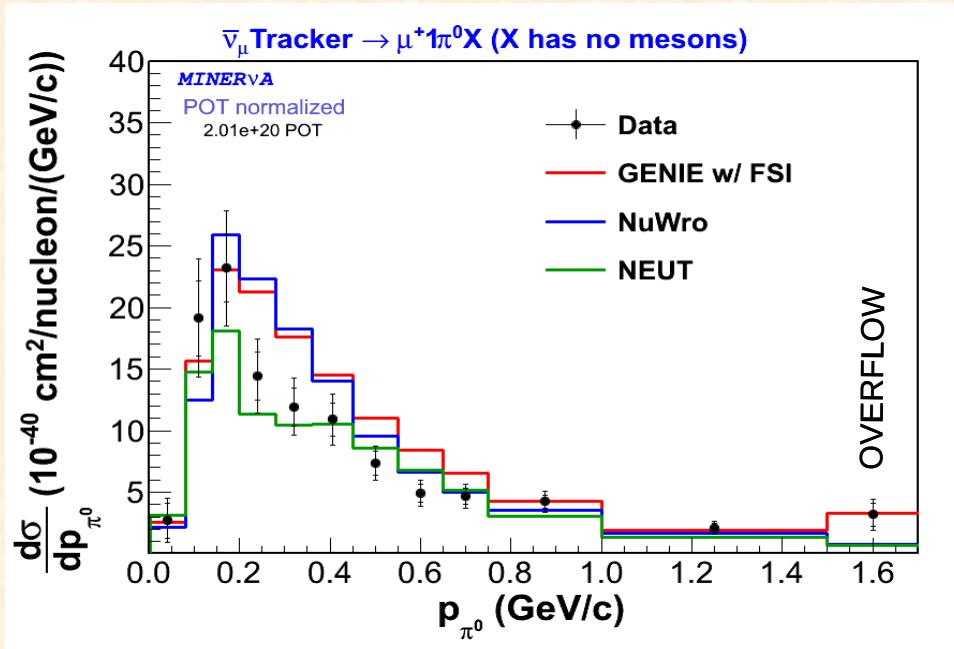
Other generators

- ◆ NEUT (Hayato, Acta Phys. Polon. B40 (2009) 2477)
 - Rein-Sehgal model with modified form factors for the primary interaction
 - Cascade model for final state interactions
 - Used by T2K experiment
- ◆ NuWro (Golan et al, Nucl. Phys. Proc. Suppl. 229-232 (2012) 499)
 - Treat Delta resonance explicitly, DIS formalism for higher mass resonances
 - Cascade model for final state interactions



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Comparison with other generators

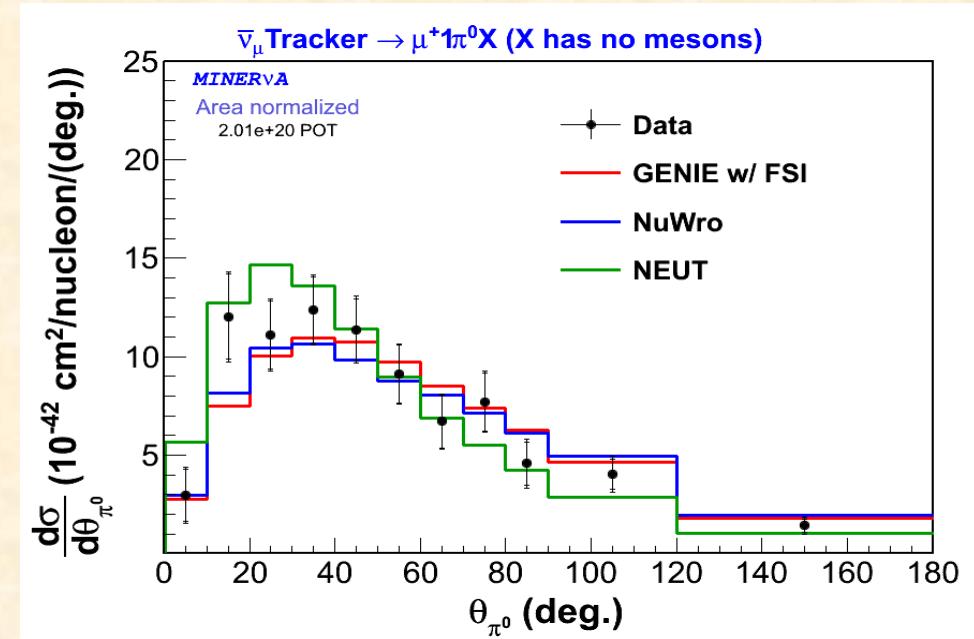
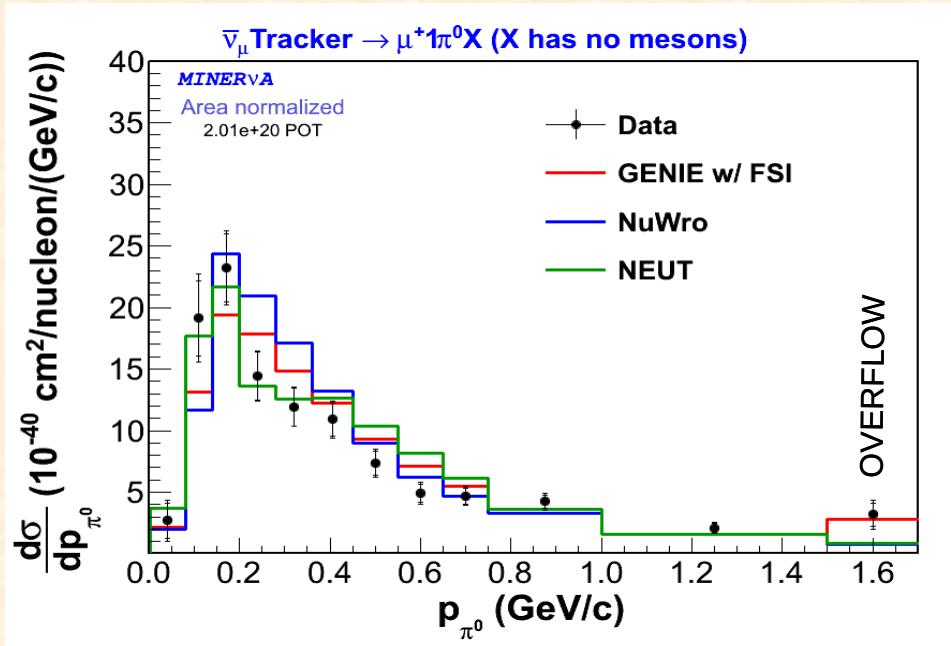




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Comparison with other generators

Shape-only cross sections



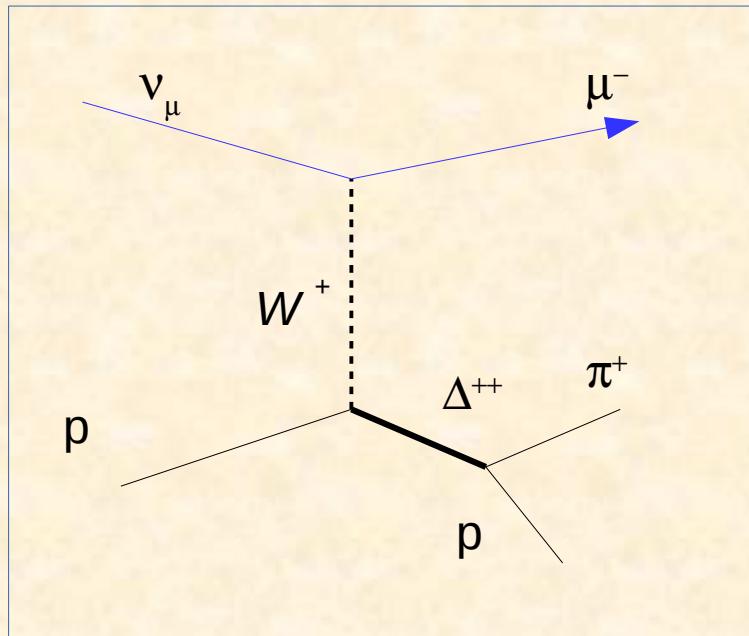


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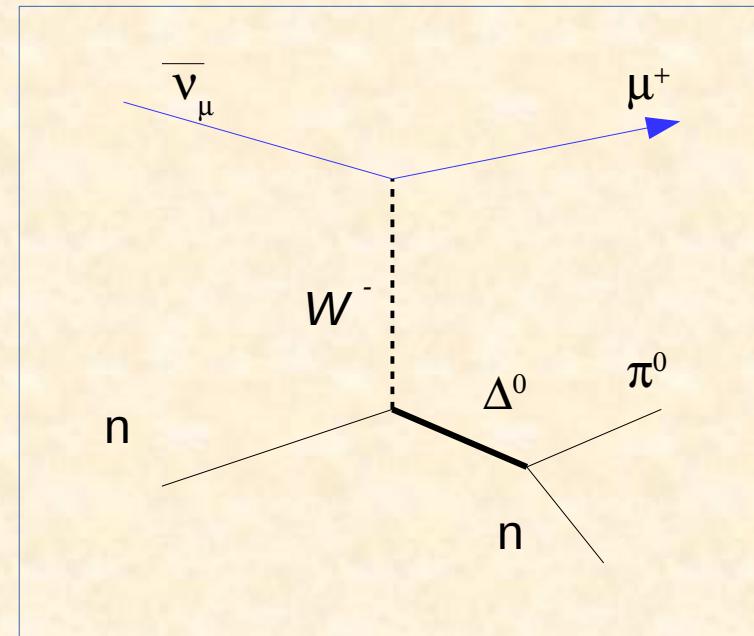
Comparison with MINERvA $1\pi^+$ production by neutrinos

- ◆ Different probes, but the media where the Δ is produced are very similar

$$\nu p \rightarrow \mu^- p \pi^+$$



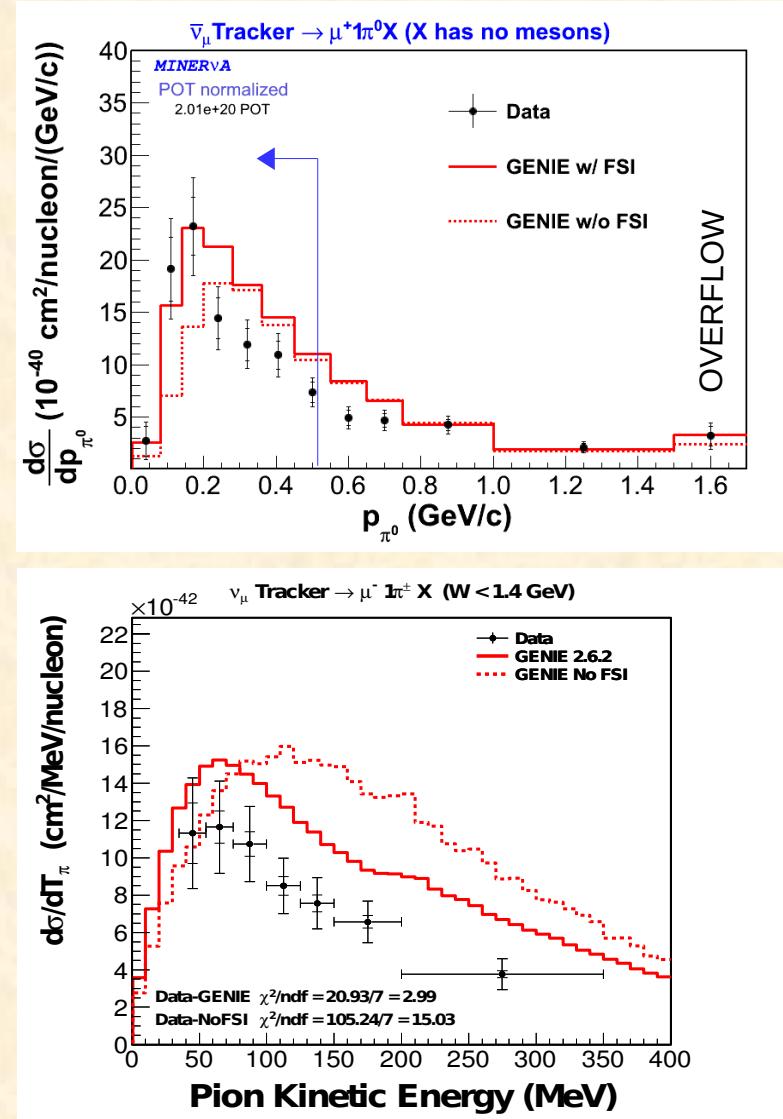
$$\bar{\nu}_\mu p \rightarrow \mu^+ n \pi^0$$





Comparison with MINERvA $1\pi^+$ production by neutrinos

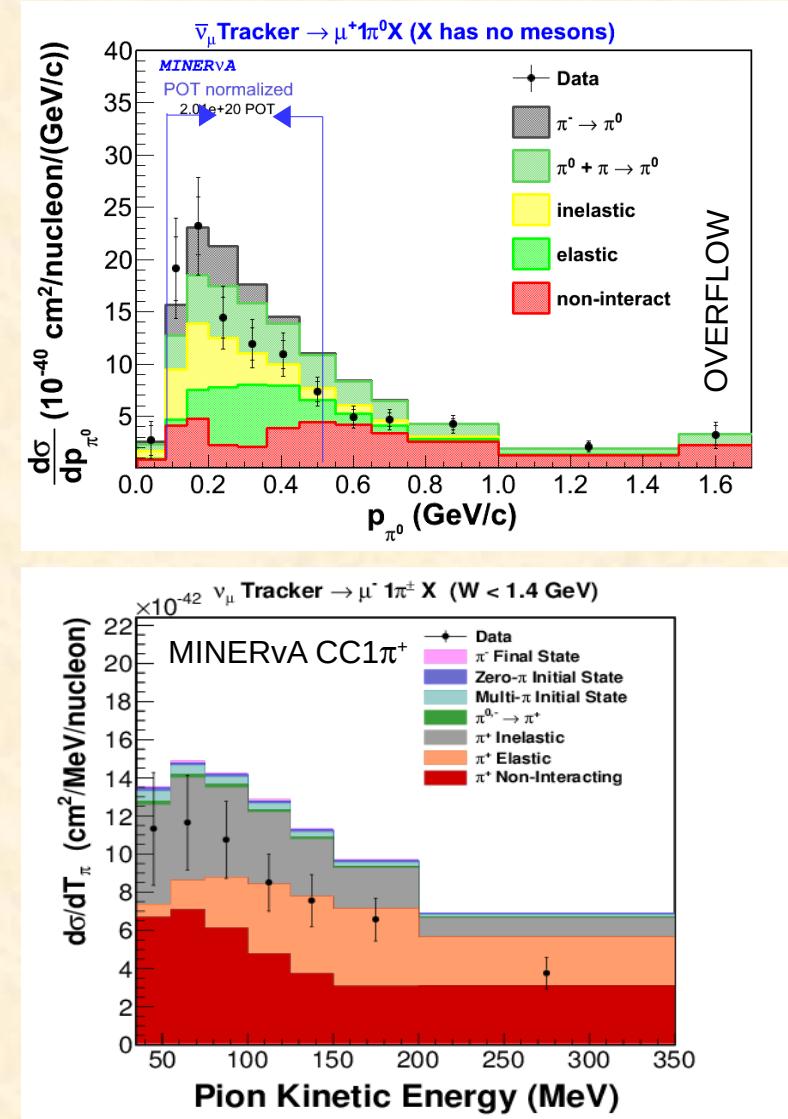
- ◆ Data agree better with GENIE with final state interactions
- ◆ GENIE: cross sections peak around 60-80 MeV kinetic energy, this is seen in both data
- ◆ GENIE: cross sections with and without FSI are very different between the two pion productions





Comparison with MINERvA $1\pi^+$ production by neutrinos

- ◆ Decomposition by final state interaction (FSI) channels
- ◆ The two pion productions have very different FSI channel contributions:
 - $1\pi^0$: $\pi^- \rightarrow \pi^0$ charge exchange
 - $1\pi^+$: no charge exchange, but more inelastic around the peak
- ◆ Measurements of different pion productions provide strong tests for generators and theoretical models





Conclusions

- ◆ We have measured differential cross sections for $1\pi^0$ production from $\bar{\nu}_\mu$ charged-current interactions on plastic scintillator as function of the π^0 momentum and angle
- ◆ Data are in better agreement when final state interactions are included
- ◆ First measurement of the differential cross sections vs π^0 kinematics for this pion production channel
- ◆ These cross sections can be used as benchmark to evaluate neutrino generator performance in π^0 production by anti-neutrinos for current and future oscillation experiments



Acknowledgments

We thank the MINOS Collaboration for use of its near detector data and the staff of Fermilab for the support of beamline, detector, and computing



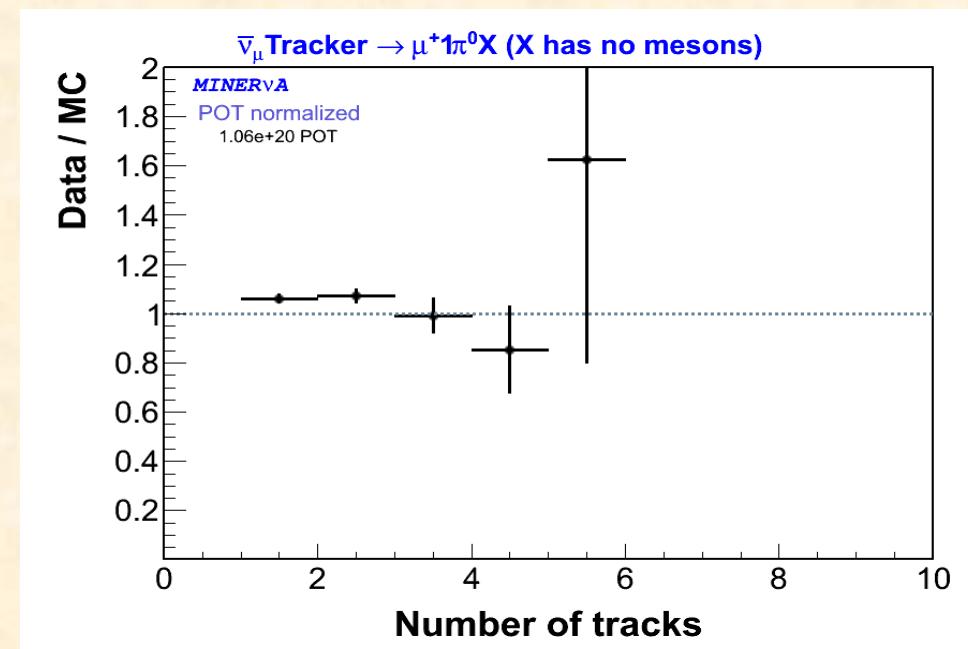
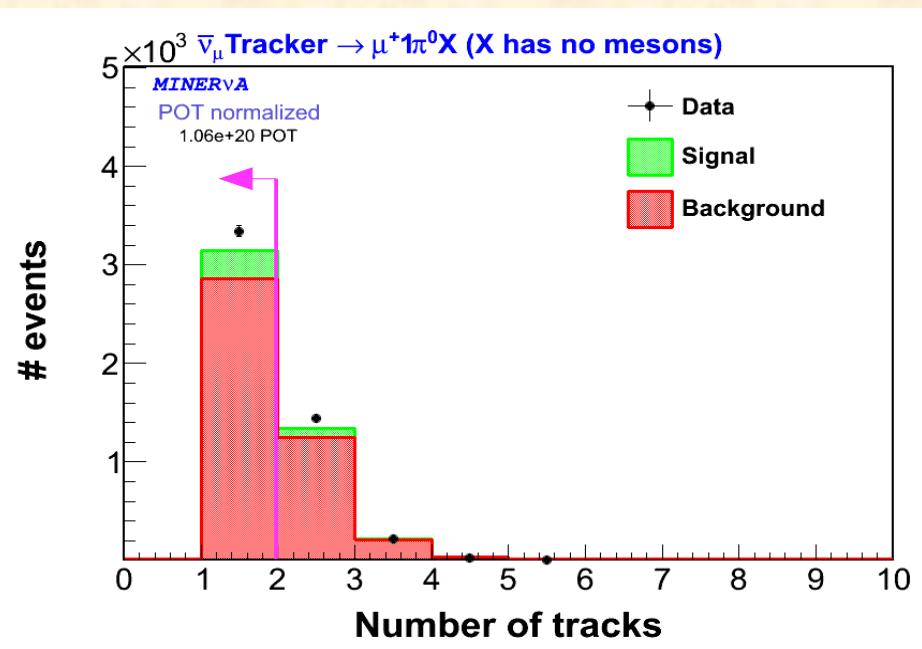
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Backup



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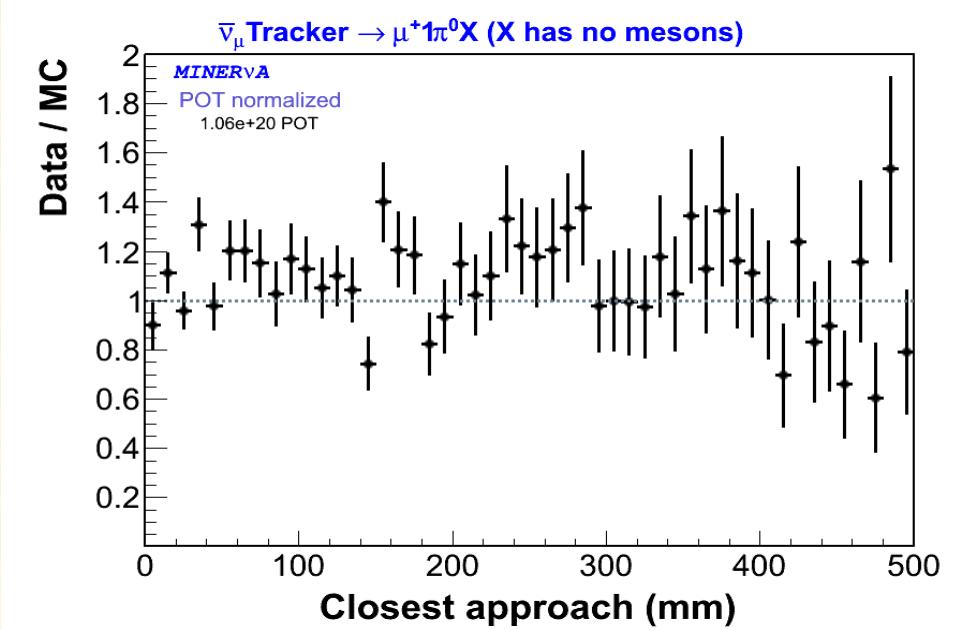
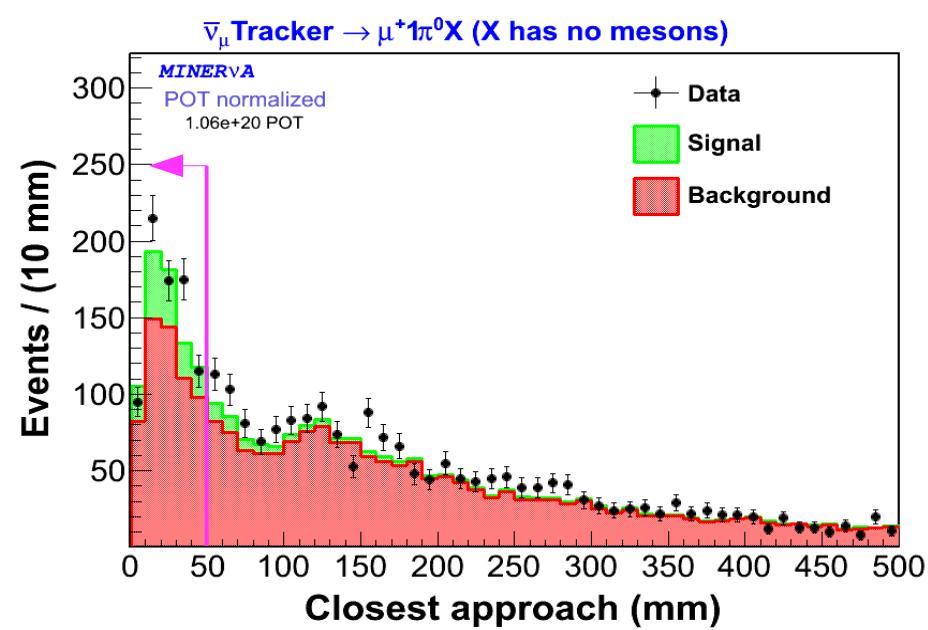
Maximum number of tracks at secondary vertices





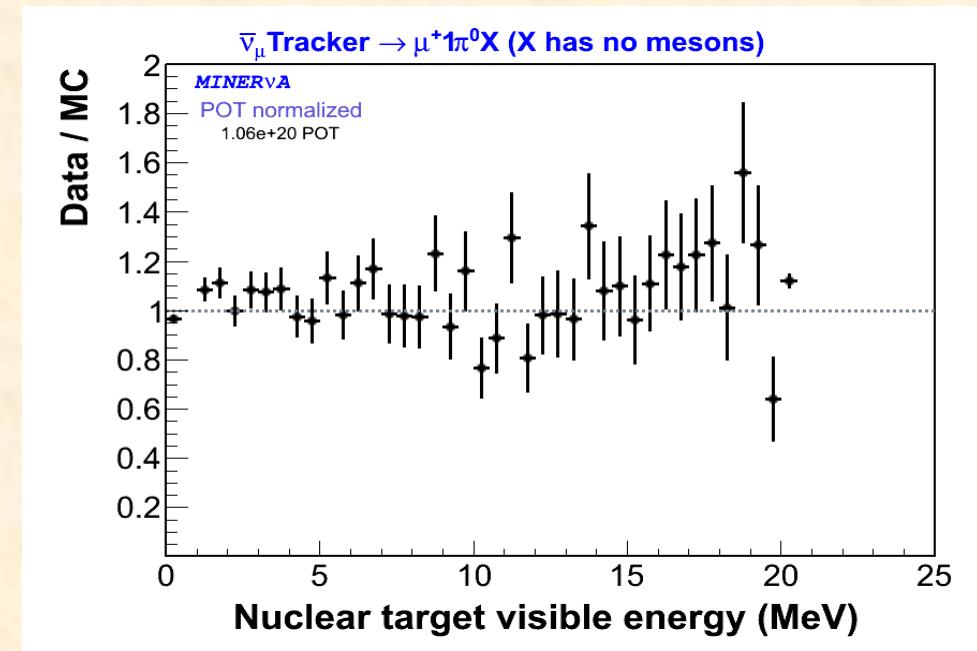
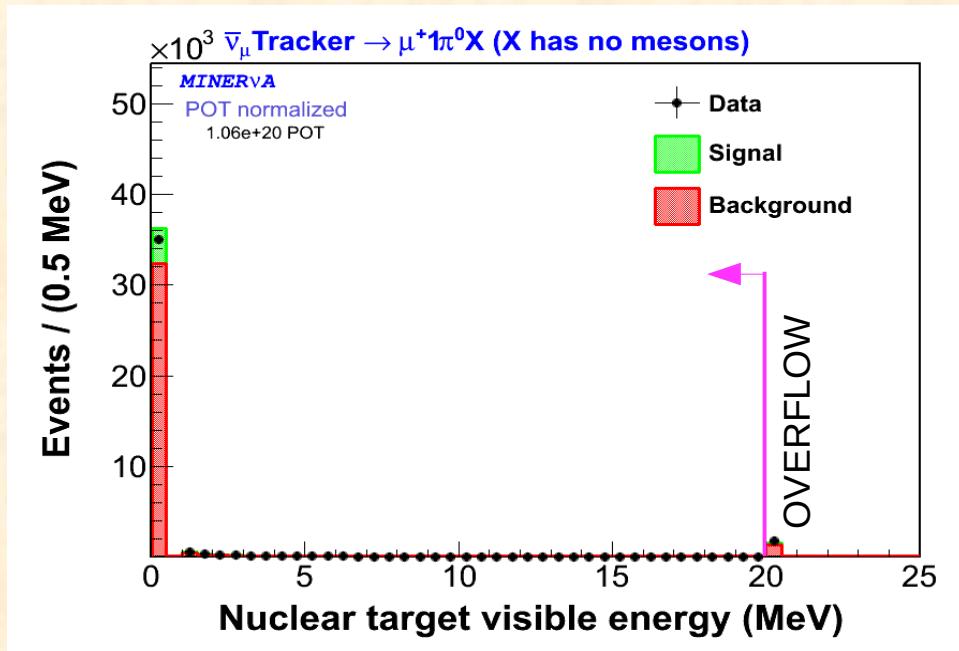
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Tracks at secondary vertices





Visible energy in the nuclear target

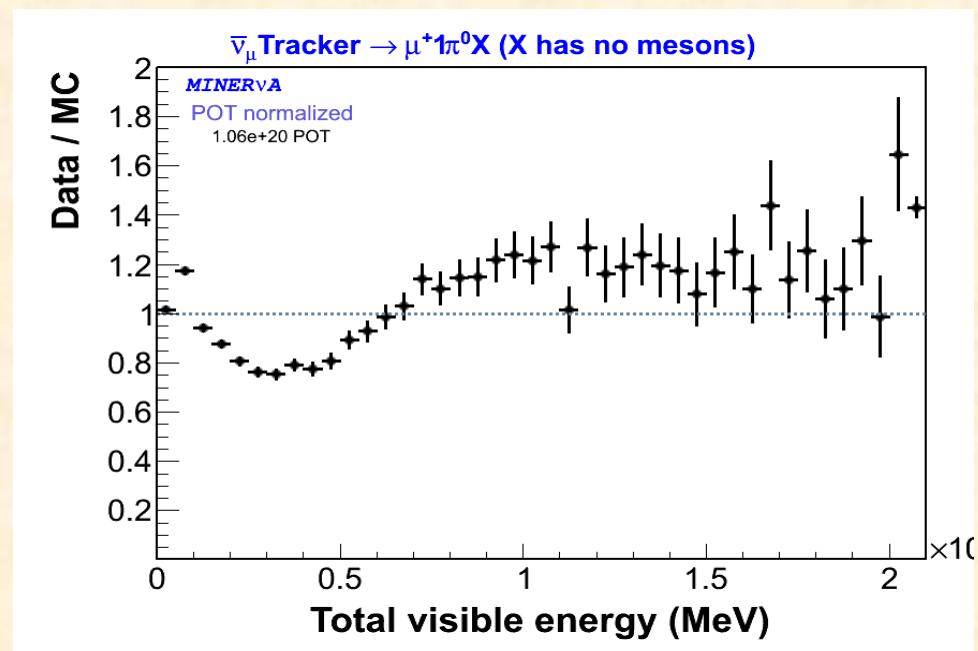
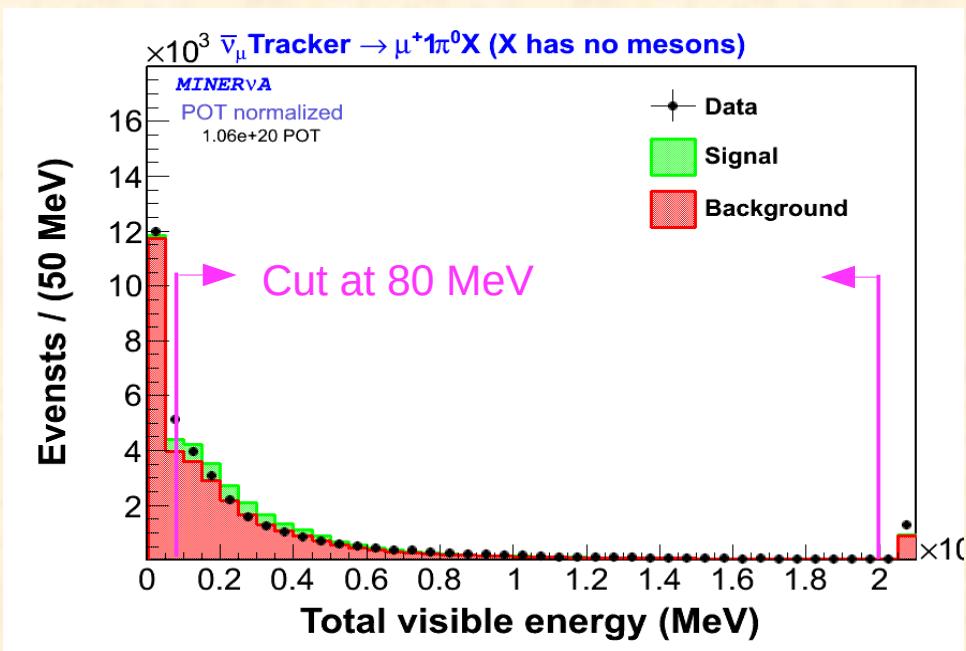


I also tried the cut at 10 MeV on the total visible energy *upstream* of the water target, the effect is very small ($< 1\%$)



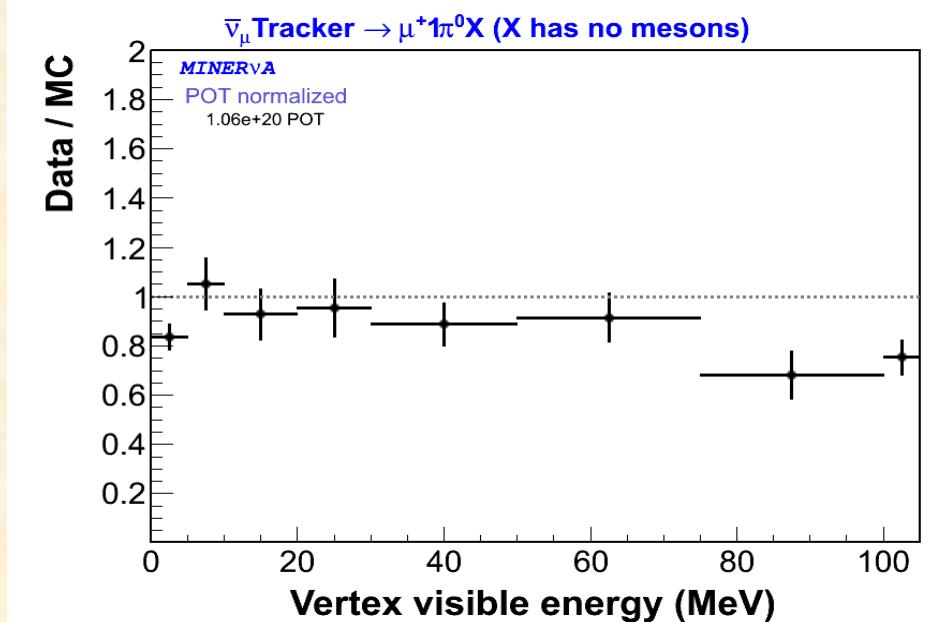
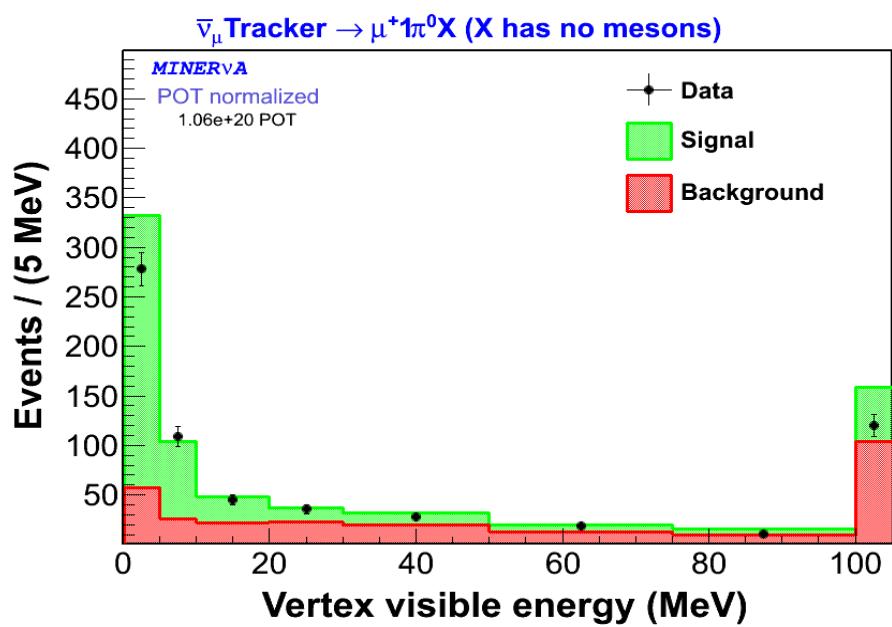
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Total visible energy in the tracker + ECAL + HCAL





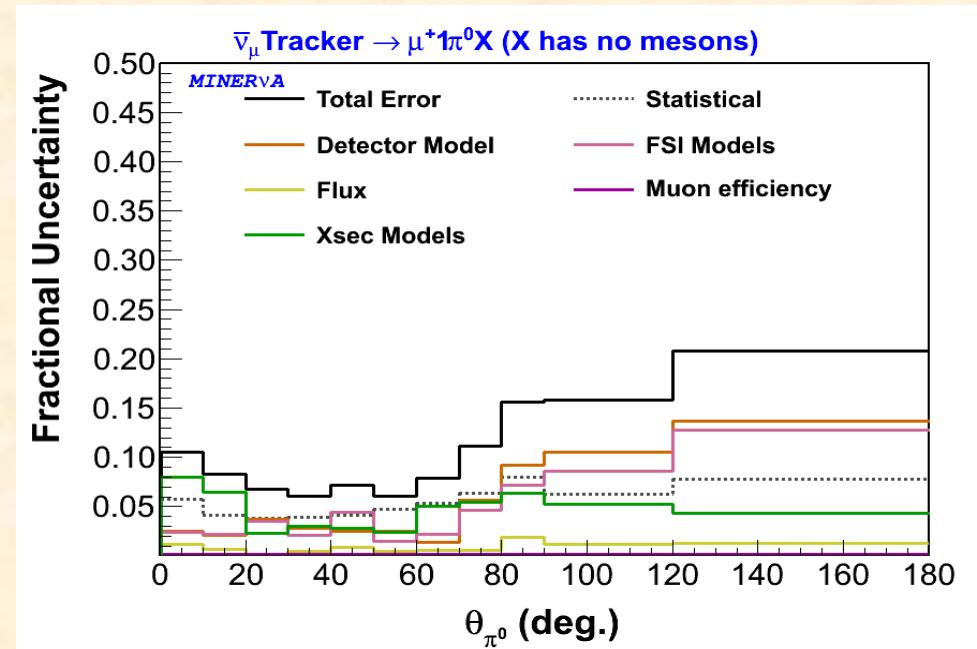
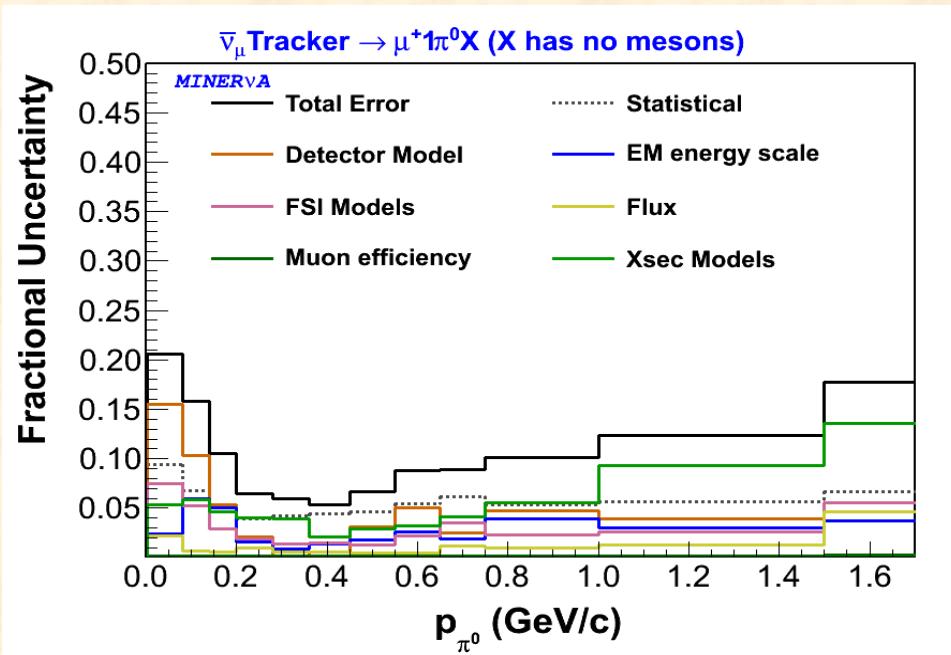
Vertex energy





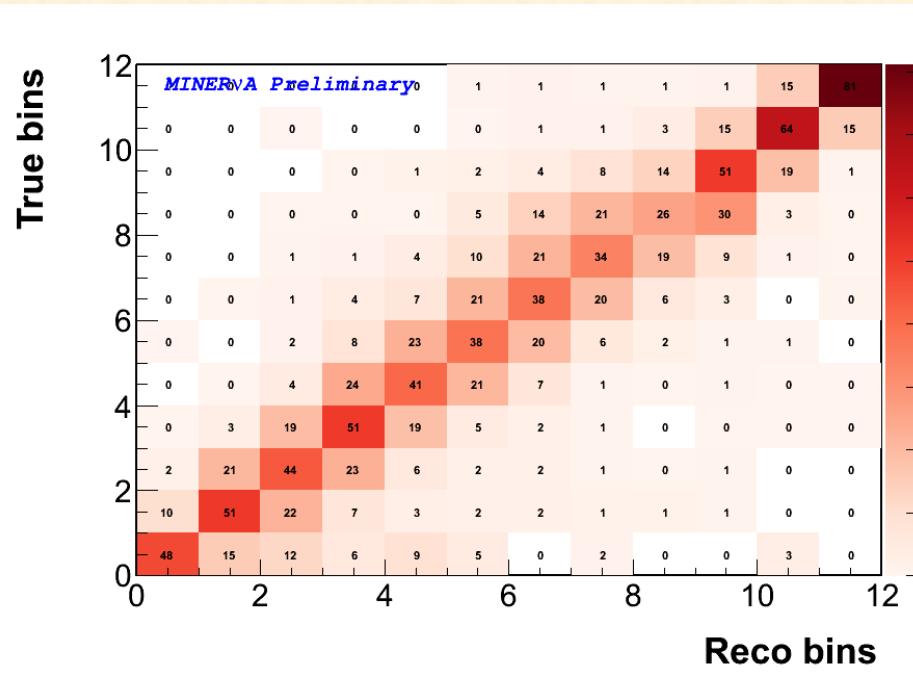
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Constrained background uncertainties

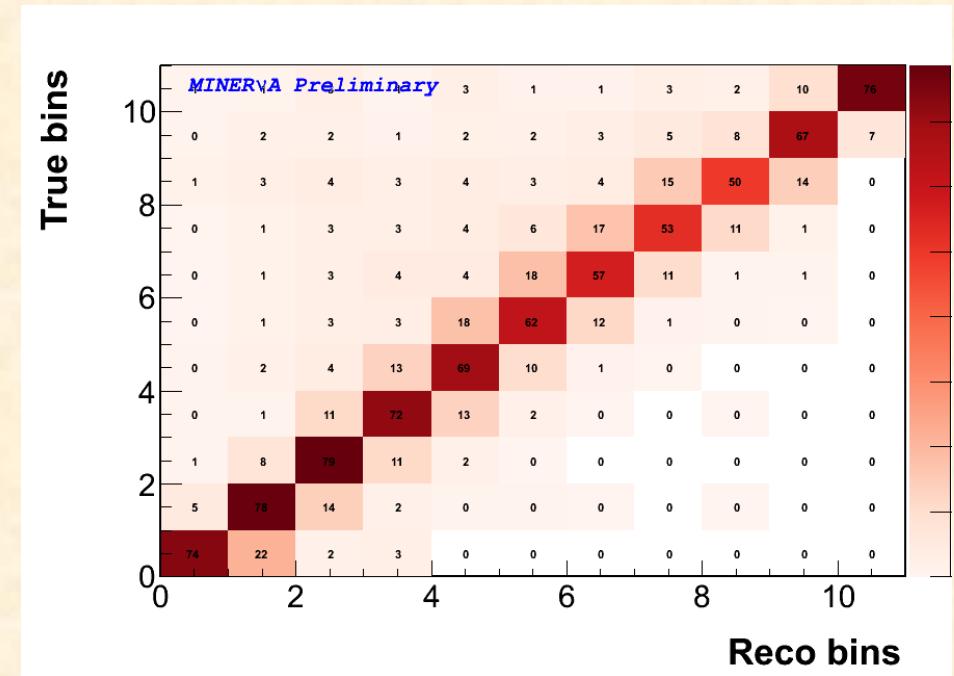




Migration matrices



Bin #	p (GeV/c)
0	0.00 – 0.08
1	0.08 – 0.14
2	0.14 – 0.20
3	0.20 – 0.28
4	0.28 – 0.36
5	0.36 – 0.45
6	0.45 – 0.55
7	0.55 – 0.65
8	0.65 – 0.75
9	0.75 – 1.00
10	1.00 – 1.50
11	OVERFLOW



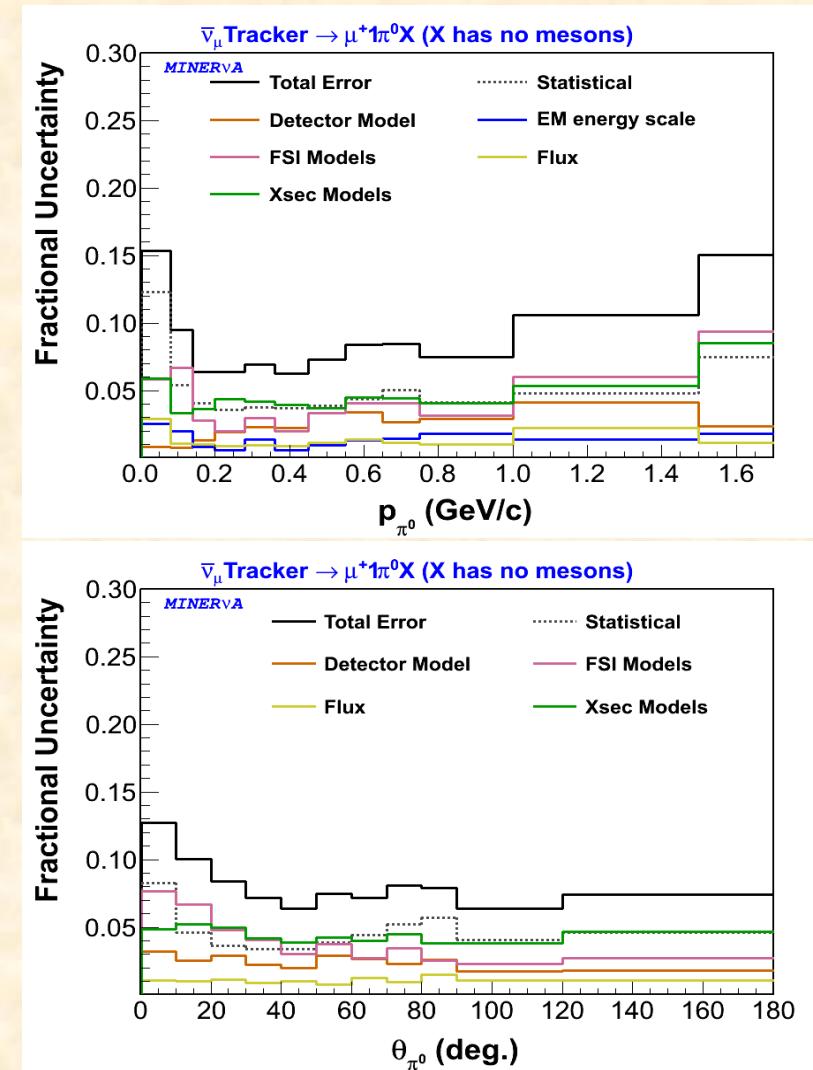
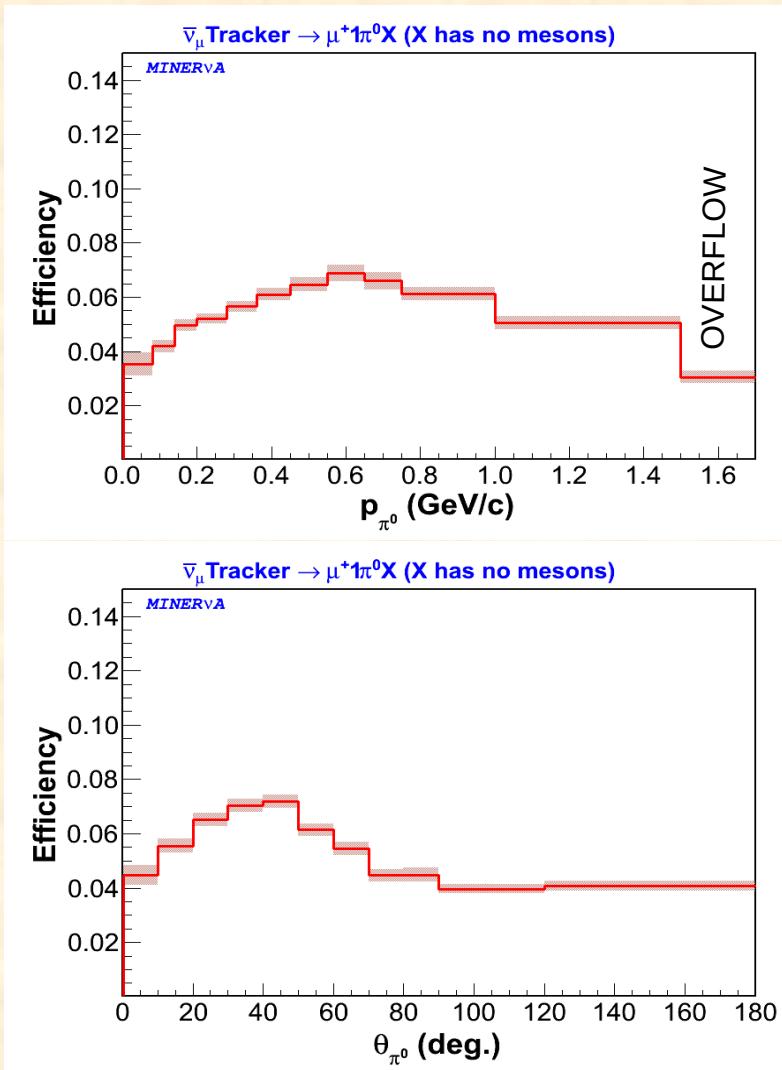
Bin #	θ (deg.)
0	0 – 10
1	10 – 20
2	20 – 30
3	30 – 40
4	40 – 50
5	50 – 60
6	60 – 70
7	70 – 80
8	80 – 90
9	90 – 120
10	120 – 180



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Efficiency with uncertainties

Efficiency curves calculated from the simulation

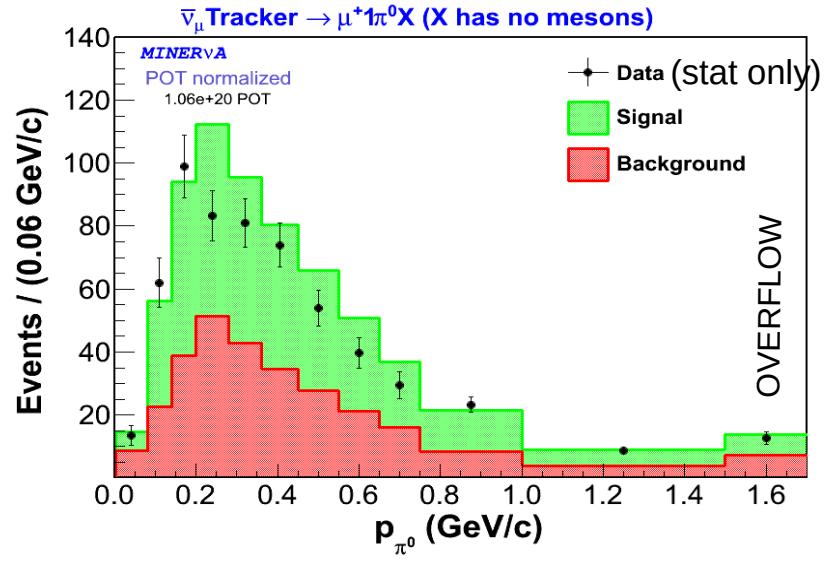




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With constrained background

BEFORE



AFTER

